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Numerical Weather Prediction

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Validation of the Mesoscale Model during periods of observed low cloud using data from the Cardington balloon facility

By M. Bush

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Met Office , Forecasting Development , Room R321, London Road , Bracknell , Berkshire ,RG12 2SZ, United Kingdom

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Mike Bush, NWP

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The Met Office

NWP

Room 344

London Road

Bracknell

RG12 2SZ

United Kingdom

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Tel: 44 (0)1344 856245 Fax: 44 (0)1344 854026 email: john.armstrong@metoffice.com

Abstract

The Met Office has a Meteorological Research Unit (MRU) at Cardington, Bedfordshire, where research is undertaken into turbulent flow using specially developed turbulence probes held aloft at various heights under a tethered balloon. In addition there is a comprehensive suite of surface instruments and a radiosonde facility (either launched on site or in the region). With these data it is possible to make a direct validation of Mesoscale Model forecasts at high temporal resolution.

This report discusses the results of a case study based validation of the Mesoscale Model during periods of observed low cloud using data from Cardington. It aims to address the following three questions:

1) Can we gain a better understanding of model systematic cloud errors by using the Cardington balloon facility?

2) Can we improve the cloud forecast? (E.g. by increasing model vertical resolution).

3) What recommendations can be provided for further work?

The thermodynamic structure of two case studies is studied in detail and in both cases the structure is found to be poorly initialised. The modelled inversions are neither strong nor sharp enough and the model is found to be too moist both above the inversion and in the sub-cloud layer. In general the model produces a good simulation of cloud, with cloud amount errors appearing to be case dependant.

In an attempt to improve the forecast, a test version of the Mesoscale Model was run with 45 levels in the vertical (the operational model has 38 levels), with five of these extra levels in the boundary layer. It was found that the sharpness of the temperature and humidity profile at the inversion was sometimes increased, leading to an increase in the amount of low cloud.

1. Introduction

Following the introduction of new cloud microphysics (August 1998) and boundary layer schemes (May 1999) into the Mesoscale Model, objective verification of total cloud cover showed an increase in the negative bias (Figure 1). This negative bias has subsequently been reduced as a result of three upgrades, the first in March 2000 and the other two simultaneously in June 2000:

i. a revision to the generation of MOPS* data in the cloud analysis

ii. introducing a parametrization of the radiative effects of horizontal inhomogeneities in cloud water path (Cahalan et al., 1994)

iii. a modification to the relationship between cloud fraction and grid-box mean RH (Wood and Field, 2000)

However the model continues to produce too few cloud forecasts of seven/eight oktas while producing too many forecasts of one to four oktas (Figure 2). Also forecasters have long complained that model forecasts of boundary layer cloud such as stratus and stratocumulus are inadequate and that model low cloud errors are the major cause of errors in surface temperature and visibility forecasts. In response to these concerns, the NWP Maintenance and Development Programme 2000/01 has specific commitments to improving Mesoscale Model forecasts of cloud and precipitation (e.g. FC03C):

"Diagnostic studies and model validation will seek to expose systematic errors in both global and mesoscale models and their likely causes. Attention will be focused on developing novel diagnostic techniques for evaluating the model performance. This will include comparison of the models against new data sources". The 2002/2003 Programme specifically includes a "Tiger Team" (FC03ER) to improve cloud forecasts.

This report discusses the results of a case study based validation of the Mesoscale Model during periods of observed low cloud using data from the Cardington balloon facility and surface site. It aims to address the following three questions:

1) Can we gain a better understanding of model systematic cloud errors by using the Cardington balloon facility?

2) Can we improve the cloud forecast? (E.g. by increasing model vertical resolution).

3) What recommendations can be provided for further work?

* MOPS = Moisture Observation Pre-processing system. Satellite imagery and surface cloud reports are blended with radar imagery to form a 3-dimensional cloud analysis for assimilation by the Mesoscale model (Macpherson et al, 1996).

A description of the observational data and a brief outline of the synoptic situation for the three case studies are given in section 2. Section 3 gives details of the model experimental set-up. Section 4 discusses the model performance and attempts to diagnose the cause of model errors. Section 5 describes the effect of (i) increasing the vertical resolution and (ii) increasing the frequency of radiation calls. Section 6 contains a summary and recommendations for further work.

2. Observational data and synoptic situation of the case studies

The Met Office has a Meteorological Research Unit (MRU) at Cardington, Bedfordshire with access to a balloon facility. Research at Cardington is undertaken into the turbulent flow in the lower two kilometres of the atmosphere using specially developed turbulence probes held aloft at various heights under a tethered balloon (Figure 3). In addition there is a comprehensive suite of surface instruments and a radiosonde facility (either launched on site or in the region). A direct validation of Mesoscale Model forecasts at high temporal resolution is therefore possible with surface site data available every seventeen minutes and model data available every five minutes (or hourly for radiation diagnostics). Only hourly model data are plotted, as this is sufficient to demonstrate the key elements of model performance. Appendix A lists the Cardington sonde, balloon and surface site data with corresponding Mesoscale Model diagnostics. Grey shading denotes data presented in this report.

The balloon is not allowed to fly if there is the slightest risk of lightning (due to the highly conducting tethering cable that trails beneath the balloon). Thus flying conditions are limited to dry days and weekdays between 7.30am and 4pm for staffing reasons. Also the balloon can only reach a maximum altitude of about 1800m and in September the stratocumulus cloud base is often above this level. With these constraints in mind it is perhaps not surprising that only three Intensive Observing Periods (IOP's) were made in cloud.

The mode of operation of the balloon was an ascent during the morning (duration approx. 90minutes) followed by a level run of at least 60 minutes and then a 90 minute descent. This was then repeated once or twice more during the afternoon. The reason for the level run lasting 60 minutes is that at the height concerned (4000 feet) the timescale for the turbulence is slow and there is a need to average covariances over at least an hour to achieve robust flux measurements.

The first IOP was the 12th of September 2000. The day at Cardington was characterised by stratocumulus and cumulus clouds with spells of both clear conditions and total cloud cover. The flow was west-north-westerly with high pressure (1018 mb) situated to the south west of Cornwall and low pressure (1006 mb) situated over the North Sea. The Mesoscale Model analysis valid at 12z is shown in Figure 4.

The second IOP was the 13th of September 2000. The pressure at Cardington had risen by a few millibars as the low pressure centre moved further away to Denmark and the high pressure area (1016 mb) became centred over Brittany (Figure 5). The day was characterised by very slack flow and a rather complicated cloud structure with different layers of stratocumulus, small cumulus and cirrus that increased through the day. The top layer of stratocumulus was observed to be above the balloon.

The third IOP was the 22nd of September 2000. The day was a classic cumulus day with cumulus developing out of a clear sky with cirrus above. Synoptically there was high pressure over Scandinavia (1035 mb) and the continent (1025 mb) with low pressure situated to the north west of Scotland (Figure 6). This produced quite a strong gradient over the northern North Sea but rather slack west south-westerly flow over Cardington.

3. Model experimental set-up

The Mesoscale Model is a limited area version of the Global Unified Model (Cullen et al. 1991) with a horizontal resolution of about 12km and 38 levels in the vertical. The cloud microphysics scheme (Wilson and Ballard, 1999) introduced in August 1998 has an explicit prognostic ice variable and transfer terms that convert one water quantity into another (the previous scheme used temperature to partition liquid and solid phases). The new boundary layer mixing scheme (Lock et al. 2000) introduced in May 1999 has an explicit entrainment parametrization and uses a plume ascent to diagnose the depth and presence of any unstable layers. Different boundary layer 'types' are defined and the appropriate K-profile mixing applied. Stable boundary layer mixing is still based on the local Richardson number. A new surface scheme called MOSES 1 (Cox et al. 1999) was introduced at the same time as the boundary layer scheme and includes the effect of soil moisture freezing.

The Mesoscale Model was re-run for the three IOP'S using a version of the model (cycle M21) that was operational at June 2000. The model was run out to T+24 from 0z without data assimilation. The choice of an analysis time of 0z allowed the model sufficient time to spin-up and yet kept the analysis of the model performance (during daytime) as simple as possible by minimising the error growth due to lead time. The model re-runs did not exactly reproduce the operational forecast due to the lack of assimilation and the use of version M21 of the model. However the main points of interest were captured.

4. Model Performance and diagnosis of model error

The general synoptic evolution of the Mesoscale Model during the three IOP'S was well handled. The observed and modelled MSLP fields at Cardington were within 1 mb of each other (even at T+24) and this implies that errors in the cloud forecast were not due to large scale errors in the modelled synoptic flow.

Before comparing the cloud forecast with observations, we begin by comparing the model with sonde and balloon ascents for the first two IOP'S to determine if there are any systematic errors in the thermodynamic structure. In the discussion that follows, the use of the word analysis refers strictly to an 'uninitialised' analysis. This is the operationally achived analysis, but unlike an 'initialised' analysis, does not contain the full impact of observations due to the time window for insertion of observation increments straddling the validity time of the analysis. MOPS cloud increments for a midnight analysis are inserted between 22.00 and 00.30 for example.

4.1 Thermodynamic structure

4.1.1 IOP 1 - 12/09/00

The model starts off from a rather poorly defined analysis (Figure 7a) with the observed inversion at 775mb-800mb not captured in the model and a poor representation of the humidity structure (in particular the placing of the dry slot). Despite this the model manages to develop and lift a new inversion, although its development lags behind the real inversion by a couple of hours (Figure 8). This lag causes an error in the vertical placing of the modelled inversion which grows from 20mb at 07z (Figure 7b) to 50mb by 11z (Figure 7c) and persists through the rest of the forecast (Figure 7d).

The inversion strength (IS) or temperature jump across the inversion is underestimated at all times by the model and at 7z and 11z the modelled inversion strength is about 75% of the real inversion strength (table 1). However the model simulation of the inversion strength is quite good in general and appears even better if the time lag is taken into consideration.

	7z	8z	9z	10z	11z	12z	13z	14z	15z
IS obs (deg)	6.6				5.4				3.5
IS model (deg)	5.0	5.2	5.1	4.5	3.8	2.6	2.0	1.6	1.1

Table 1: Inversion strength values for IOP 1

The modelled inversion is spread out too much in the vertical (Figure 8). This spread can be quantified by a parameter called the Inversion Base Sharpness or IBS (Price 1999). It is defined as being the vertical distance travelled in moving between a typical boundary-layer lapse rate (i.e. saturated adiabatic lapse rate) to one of the overlying inversion. It gives a measure of thickness of the entrainment zone between the boundary layer air below the inversion and the dry overlying air. The IBS parameter is adapted here to look at the modelled inversion.

	7z	8z	9z	10z	11z	12z	13z	14z	15z
IBS obs (mb)	10				13				7.5
IBS model (mb)	20	20	31	31	31	21	23	15	31

Table 2: IBS values for IOP 1

The modelled IBS values for IOP 1 are a factor of 2.0 to 4.1 greater than the observed values (Table 2). This is because the modelled inversion is spread out between three or four model levels while the observed inversion spans less distance than two adjacent model levels. The effect of increased vertical resolution on the IBS is investigated in section 5 where it will be shown that the simulation of the inversion can be improved.

The model generally does well at capturing the large temporal evolution of the humidity structure although it is too moist both below the modelled inversion and also in the dry slot immediately above the observed inversion (Figure 7c). Balloon specific humidity data (Figure 9) indicates that this error was of the order of 0.5g/kg between 11z and 12z. At this time the boundary layer (below 915mb) is also too cold by 2 to 3 degrees (Figure 7c) and so the model relative humidity errors are due to a combination of errors in both temperature and specific humidity. By 15z the simulation of the dry slot above the observed inversion was much improved (Figure 7d).

4.1.2 IOP 2 - 13/09/00

The model analysis is too moist both in the dry slot above the inversion at 750mb and also in the 1000mb-850mb region (Figure 11a). The model makes an attempt to capture the inversion at 750mb, but it is far too weak. As in IOP 1 however, the model manages to develop a strong inversion by 15z/16z (Figure 12) despite starting from a relatively poor analysis.

The model severely underestimates the inversion strength in IOP 2 during the morning. The simulation improves during the afternoon and by 15z/16z it reproduces 75-80% of the real inversion strength (Table 3).

	7z	8z	9z	10z	11z	12z	13z	14z	15z	16z
IS obs (deg)	5.0				5.7				5.4	
IS model (deg)	0.5	0.7	0.5	0.7	0.9	2.1	2.9	3.1	3.6	4.4

Table 3: Inversion strength values for IOP 2

The observed IBS values are extremely small in IOP 2 with the modelled IBS values being up to 12 times larger than the observed values (Table 4). The modelled inversion becomes sharper during the afternoon but remains too spread out. The fact that the modelled IBS values are greater than in IOP1 possibly reflects a greater amount of entrainment in the model in this case study.

	7z	8z	9z	10z	11z	12z	13z	14z	15z
IBS obs (mb)	4				15				4
IBS model (mb)	50	50	50	50	50	31	31	31	31

Table 4: IBS values for IOP 2

The poor handling of the inversion structure during the morning is reflected in the poor representation of the saturated layers at both 800mb and 900mb (Figure 11b). In general the model humidity structure remains too moist in the sub-cloud layer (Figure 11c, Figure 11d). The model also appears to be too well-mixed (Figure 13b).

4.1.3 Summary of thermodynamic structure

Systematic errors common to both case studies are:

- Model analyses are poorly initialised (evident even in the operational forecast)
- Modelled inversions are not strong enough
- Modelled inversions are not sharp enough
- Model too moist both above inversion and in sub-cloud layer

Errors specific to IOP 1:

- Modelled boundary layer evolves too slowly causing the modelled inversion to be misplaced in the vertical

4.2 Cloud Structure and evolution

Manual cloud observations were taken between the hours of 7z and 16z and are accurate to the nearest okta. The precise timings of the observations reflect the speed with which the cloud cover was changing and the fact that the observations were not taken at regular clockface intervals.

4.2.1 IOP 1

The Mesoscale model generally produces a good cloud forecast. At 07z a bank of stratocumulus cloud (Figure 14a) stretches from Cardington (complete cover) down to London. The model successfully simulates the cloud present over the tips of Norfolk and Kent and also over Lincolnshire (Figure 14b). In contrast the model has too little cloud to the South and East of Cardington. At Cardington itself the model has 1-2 oktas too little cloud at 07z (Figure 15) causing the modelled 1.5m temperatures to be too cold (Figure 16).

The situation abruptly changes at 08z when the observations show a clearance of the cloud over Cardington as it advects to the south and east. Although the model shows a reduction in low cloud amount at 08z, it now has too much low cloud until 11z (Figure 15). This has the effect of cutting the levels of solar radiation reaching the ground and so causing surface temperatures to lag behind observations (Figure 16). This is a possible cause of the lag in the development of the modelled inversion.

There is a marked change in the observed cloud cover between 12z and 13z as the cumulus/stratocumulus that has built up since 08z dissipates (Figure 18), possibly as a result of the three oktas of cirrus reported reducing surface driven convection. The modelled low cloud amount decreases realistically although at certain times (e.g.14z) there continues to be an overestimate of low cloud amount. High cloud amounts are difficult to verify due to the lack of observations.

The model has a small amount of cloud in its lowest model level (35ft) at 3z (Figure 17) although the largest amounts are at model level 7 (2000ft). This agrees with observations from the cloud base recorder which show cloud base starting off at about 2000 ft (model level 7) and reaching 3500ft (model level 9 or 10) by about 11z (Figure 18). The model keeps its largest cloud amounts at model level 7 so that by 11z there is a misplacement by at least two model levels. The model cloud base is too low as a result of the misplaced inversion and this error grows during the morning as discussed in 4.1.1. This causes too much moisture to be concentrated in the lowest levels (Figure 7c) and spurious cloud to form.

By 15z the largest cloud fraction was at 5,400 ft (model level 12) compared to about 7,400 ft (model level 14) in the observations. Again this height difference corresponds to the 50mb displacement of the modelled inversion at this time and the excessive amounts of small cloud fraction below 5,400 ft (Figure 18) are consistent with the model being too moist below the inversion.

4.2.2 IOP2

The model again produces a generally good cloud simulation. The observed cloud evolution was complicated at 07z with 5-6 oktas of stratocumulus at two distinct levels. A third cloud layer then formed by 09z. The model underestimates the cloud amount between 7z and 9z (Figure 19) and this is due to the poor handling of the inversion humidity structure and the saturated layer at 900mb (discussed in section 4.1.2). The observed low cloud cover gradually increased until about 12z (as the upper layer of stratocumulus became thinner and cumulus field deepened). The model low cloud fraction reproduced this increase remarkably well (Figure 19). However the gradual build up of cirrus during the morning (2 oktas at 8z to 7 oktas at 13z)

dramatically reduced the amount of surface driven convection and so low cloud amounts decreased sharply between 13z and 14z, increasing surface temperatures (Figure 20).

The model simulation of this decrease in low cloud amount was poor and may well be due to errors in accurately simulating high cloud amounts. The model overestimated high cloud amounts during the morning (Figure 19 top panel) and this is consistent with the underestimate of low cloud amounts (due to reduced short wave radiation). This situation was then reversed between 13z and 14z when the model did not have sufficient high cloud and so low cloud amounts were overestimated (Figure 19 bottom panel) and screen level temperatures were underestimated (Figure 20).

The modelled cloud amount in a layer (Figure 21) shows good agreement with the observations of cloud base (Figure 22). The largest model cloud fractions at 2,600 ft at 4z and 5z and the rising cloud base from 1,500 ft at 9z to 3,500 ft by 12z correspond well with the observations at these times. Also the large model cloud fractions at about 5,300 ft are consistent with the upper layer of stratocumulus observed at 6,000 ft. The performance is worse during the evening with the cloud base too low in the model and an unrealistic break in the cloud deck between 18z and 20z. This may be linked to the large amount of upper level cloud in the model at this time (cloud fractions of 1.0 at 10,000 ft) reducing model convective activity and hence allowing the break-up of the lower cloud deck.

4.2.3 IOP 3

The model gives a good simulation of the descending cloud base from 3z to 7z (Figure 23) but fails to capture the second cloud base descent from 19z to 23z (Figure 24). There is also erroneous low cloud in model levels 1 to 5 during the morning from about 5z to 8z and this is associated with the model being too moist below 850mb (not shown). The model removes its remaining low cloud by 11.30z and this causes the modelled screen level temperature to rise too much (Figure 25).

4.2.4 Summary of cloud structure and evolution

In general the model produces a good simulation of cloud base with the complicated evolution in IOP 2 particularly well handled. Cloud amount errors appear to be case dependant with no evidence of errors systematic to the three IOP's.

Errors in IOP 1:

- Overestimate in model cloud amount from 08z onwards leads to an underestimate in 1.5m temperatures.

- Model cloud base too low as a result of misplaced inversion.

- Spurious model cloud in sub-cloud layer as result of moist bias.

Errors in IOP 2:

- Overestimate in model high cloud amount leads to an underestimate in low cloud amounts.

4.3 Radiative fluxes

Due to instrumental problems, only the results for IOP 1 are discussed.

4.3.1 IOP 1

The net down short wave (SW) flux at the surface is quite well simulated by the model (Figure 26). The model values rise too quickly at dawn and are then underestimated from 08z until just before 12z. This is consistent with the model having too little low cloud at dawn and then too much low cloud until 11.30am (Figure 15). The situation with respect to low cloud was quite complicated during the afternoon, but SW flux errors (e.g. underestimate at 14z) are consistent with cloud cover errors (positive at 14z).

The net downwelling long wave (LW) flux at the surface (Figure 27) reveals a large discrepancy between the model and observations. The observed values are more negative (i.e. greater net LW upwelling flux) than the modelled values, particularly during daylight hours (between 8z and 17z). This result can be partly explained by the underestimate in modelled screen level temperatures (Figure 16). However there is a strong suspicion that the radiometers were suffering from heating problems (emission of their own LW radiation) and so were giving misleading results.

The net radiometer has a different calibration for long wave and short wave components and different calibrations on its upper and lower domes and so there is also the possibility of out of date calibrations. The splitting of the LW into its upwelling and downwelling components further increases suspicions about the quality of the observed values. The values for the downwelling component (not shown) are phenomenally low (125 W/m^2) compared to climatological values which never fall below 200 W/m^2 even in clear sky conditions in this country. The decrease in the upwelling values (Figure 27) at sunrise implies a surface cooling (sigma T^4) - not observed in the temperature trace (Figure 16). It is possible that these errors are due to uncertainties in knowing the dome temperature.

4.3.2 Summary of radiative flux measurements

- SW flux errors are consistent with low cloud errors.

- LW flux errors are considerable - however there is a strong suspicion that the observational radiometer data is misleading.

- LW instrumental problems include heating of the radiometers (and hence emission of their own LW flux) and accurately knowing the dome temperature so that upwelling and downwelling components can be correctly partitioned.

4.4 Sensible Heat and Moisture Flux Profiles

One of the main assets of the balloon is the ability to make turbulent flux measurements while performing a 'level run'. These can be compared with the model turbulent fluxes to see whether any systematic errors are present. Turbulent flux errors can lead to errors in the thermodynamic structure of the boundary layer and hence to the evolution of the cloud structure.

Unfortunately during the period of the first two IOP's, the balloon was experiencing problems with getting enough lift and so the number of probes attached was limited to two. During IOP3, however, five probes were attached allowing a better comparison of the model with observations (especially lower down in the atmosphere below the observed inversion). We will therefore restrict our analysis to IOP 3.

4.4.1 IOP 3

Sensible Heat Flux Profiles

The sensible heat flux profiles during the morning of IOP 3 show a reasonable agreement between the model and observations to within an accuracy of 20 W/m^2 at 11z (Figure 28a). This accuracy figure reflects the fact that the value of the observed turbulent fluxes is dependent on the detrending timescale applied to the vertical velocity used in the flux calculation. Values for the whole level run can be calculated or the level run can be split into segments and an average value for each segment calculated. The error bars grow as one moves up into the inversion region as the inversion dynamics (gravity waves etc.) start to dominate the signal. It is for this reason that only the observations from two of the probes have been included in Figure 28a. Two other probes were located within the inversion region and one other had magnetometer problems. It is suggested that at least five probes be placed between the surface and 0.75 times the boundary layer height for future NWP investigations.

During the afternoon the agreement between the model and observations is less good with the model values being larger than the observed values by greater than 20 W/m^2 at 15z (Figure 28a). This is consistent with balloon observations that show the model warms the boundary layer too much during the afternoon. The modelled entrainment fluxes at the inversion are suspiciously large. They should be 0.2 times the surface value and yet they are of the order of 100 W/m^2 at midday with surface values of around 200 W/m^2. Surface fluxes of heat are generally well predicted although the model values are overestimated during the afternoon (Figure 28b). The model does not capture the high temporal variability of the observations.

4.4.2 IOP 3

Moisture Flux Profiles

The observed moisture flux values at 11z do not agree well with the modelled moisture flux profile at 11z, but there is reasonable agreement with the 12z model profile (Figure 29a). It is difficult to verify the variability in the model profiles with the available observations (unlike at the surface). The observed fluxes at 15z agree better with the model profile. The observational error bars are estimated at 2e-05 kg/m^2/s. Surface fluxes of moisture are generally well predicted although the model values are overestimated during the afternoon (Figure 29b). The model does not capture the high temporal variability of the observations.

4.4.3 Summary of turbulent flux measurements

- Sensible heat fluxes during the morning of IOP 3 agree with observations to within 20 W/m^2. There is poorer agreement during the afternoon.

• Of the five probes carried in IOP 3, two were within the inversion region and one failed leaving just two probes to make more useful comparisons with the model.

• Probes placed at the inversion do not give stable measurements as a result of the highly localised nature of this region. Gravity waves for example can dominate the signal. For future NWP studies, at least five probes should be placed between the surface and 0.75 times the height of the boundary layer top.

• The modelled inversion fluxes seem unrealistically large.

• Surface fluxes are generally well modelled although the high temporal variablity is not captured in the model.

4.5 Diagnosing the cause of the model errors

The obvious starting point is to look at the analyses and try and understand why the model started from a poor initial state.

4.5.1 Analysis errors

Comparing the T+15 Mesoscale Model forecast (Figure 30a) valid at 15z on 12/09/00 with a T+3 forecast valid at the same time (Figure 30b), it is clear that the T+3 forecast has the inversion better placed in the vertical. However the simulation of the dry slot above the observed inversion is worse (too moist). This could be due to an incorrect specification of the observation error covariances, a problem with MOPS or simply from a lack of vertical resolution. The fact that the model was run from and compared to an uninitialised analysis (as discussed at the beginning of section 4) may also have contributed to the errors although the operational run showed similar characteristics.

4.5.2 Inversion sharpness errors

There are two possible reasons why the model IBS values are larger than the observed values. The first is a lack of sufficient vertical resolution (the observed inversion spans as little as 10-20mb (section 4.1.1)), and this is investigated in section 5. The second is that the model entrains too much as a result of an incorrect specification of the entrainment velocity. Considine and Curry (1998) propose the following relation between IBS and the entrainment velocity, w_e

$$\frac{IBS}{h} = c\frac{w_e}{\sigma_w}$$

where h represents the depth of the mixed layer, σ_w represents the vertical velocity variance and c is a constant. The error bars in the specification of the modelled entrainment velocity may be as high as 50% (Lock, personal communication).

4.5.3 Lifting dew-point analysis

Lifting dew-point (or ITd) is defined as the dew-point lower boundary layer air would have if it were to rise directly to the inversion base (Price 1999). It can be compared with the in-situ there to determine whether cloud is expected or not. The evolution with time of both the in-situ temperature and ITd then gives an idea of whether the cloud (if present) is likely to thicken or to disperse. This concept is applied to both the

observed and modelled thermodynamic profiles and in the latter case the ITd is calculated at the level of the modelled inversion.

	IOP 1 7z	IOP 1 11z	IOP 1 15Z	IOP 2 7z	IOP 2 11z	IOP 2 15z
T obs (deg)	8.5	7.6	2.8	2.0	3.5	4.3
ITd obs (deg)	9.4	8.0	6.5	8.9	8.7	6.5
T model (deg)	11.0	10.0	6.3	6.1	4.3	4.3
ITd model (deg)	11.3	10.1	8.4	8.9	8.0	8.8

Table 5: In-situ temperature (T) and lifting dew-point (ITd) values for IOP 1 and IOP 2

It is clear from table 5 that it is not possible to make any conclusions about cloud growth/dispersal, as there are not enough observations. Also the theory assumes a cloud-surface coupled system whereas the actual presence of cloud also depends on local conditions such as entrainment rate. Therefore this method might be better suited to comparing model convective cloud rather than layer cloud.

5. Sensitivity tests of the Mesoscale Model

5.1. The impact of increased vertical resolution

The control (operational Mesoscale Model) has 38 levels and 14 boundary layer levels. The test run has 45 levels and 19 boundary layer levels. The extra resolution is put in between approximately 950mb and 600mb (Figure 31) to maximise the impact on the handling the inversion and boundary layer structure. The two runs do not differ above 600mb.

5.1.1 Impact on IOP 1

The main differences in the thermal structure in IOP1 are seen in the period T+7 to T+15 (7z to 15z). The test run (dashed) has a sharper inversion compared to the control run (solid) at most times (Figure 32 and table 3). However there is little impact on the misplacing of the modelled inversion height. The fact that the test run has a sharper inversion than the control shows that the insufficient vertical resolution of the control run does indeed partially account for the error in IBS values (section 4.1.1).

	7z	8z	9z	10z	11z	12z	13z	14z	15z
IBS obs (mb)	10				13				7.5
IBS model control	20	20	31	31	31	21	23	15	31
IBS model test	22	22	22	22	30	22	15	7.5	30

Table 3: IBS values for IOP 1

The effect on relative humidity was to sharpen up the profiles leading to increased

values at the inversion (Figure 33). However this did not result in a better agreement with observations because the misplaced inversion was already causing too much moisture to be concentrated in the lowest layers.

The increase in inversion relative humidity values not surprisingly fed through to the cloud forecast (Figure 34). There was a general increase in the low cloud amount over Cardington and this verified worse against observations (e.g. around 8z and 13z). At times the increase in cloud verified better (e.g. at 7z). There was no improvement to the main error in the control run - that of the cloud base being too low due to the misplaced inversion (Figure 35).

5.1.2 Impact on IOP 2

The largest impacts on the thermal structure were again during the middle of the day and particularly striking at 14z and 15z (Figure 36). The test run (dashed) is in much better agreement with the 15z radiosonde ascent than the control run. The test run inversion is not only sharper (table 4) at this time but stronger. The error at 800 mb from is halved from two degrees to one degree.

	7z	8z	9z	10z	11z	12z	13z	14z	15z
IBS obs (mb)	4				15				4
IBS model control	50	50	50	50	50	31	31	31	15
IBS model test	60	60	60	60	30	30	15	15	7.5

Table 4: IBS values for IOP 2

Looking at the relative humidity profiles, the test run performs better than the control run in the dry slot above the inversion having a sharper gradient (Figure 37). However the formation of the doubly saturated layer around the inversion is handled less well in the test run than in the control run at 12z and 13z.

The effect on cloud was neutral. The increase in low cloud at 07z from 1 okta in the control run to 3 or 4 oktas in the test run (5-6 oktas observed) verified better while the decrease in low cloud amount at 12z and 13z verified worse (Figure 38). There was little change in either high cloud amounts (Figure 38 top panel) or to the prediction of cloud base (Figure 39).

The general lack of positive impact of increased vertical resolution on cloud forecasts was disappointing. However there are a number of aspects of the change that may not have been done in an optimal way. The choice of levels for the extra vertical resolution resulted in a less smooth spacing between levels (Figure 31). This is not good numerically. Also there is probably quite a lot of sensitivity to the choice of constants (such as the profile of critical relative humidity).

More case studies and sensitivity tests are required to fully explore the potential benefits of increased resolution.

5.1.3 Summary of the impact on model performance of increased vertical resolution

- Increased vertical resolution between 950mb and 600mb increases the sharpness of

the temperature profile at the inversion. IBS error reduced.

- No impact on the vertical misplacement of the inversion in IOP 1
- The relative humidity profile at the inversion was sharper in IOP1 but not in IOP2.
- The low cloud amount was increased in IOP1 and this verified worse on balance.
- There was no overall increase in low cloud amount in IOP2. The cloud forecast verified better at some time frames and worse at others.

5.2 The impact of calling radiation more frequently

Both longwave (LW) and short wave (SW) radiation schemes are called every hour in the operational Mesoscale model. In the test run (DAMBK) both LW and SW radiation schemes are called every 30 minutes - twice as often. The reason for doing this was to test the sensitivity of the forecast to the frequency of radiation calls and to see what effect there was on errors that might be associated with radiation.

The effect on IOP 1 was small and so the experiment was not repeated for the other case studies. There was an improvement to the forecast of the net downwelling surface SW radiation from sunrise to 07z (Figure 40), but a mixed signal during the rest of the day. There was a negligible impact on the net downwelling LW radiation and on screen level temperatures.

6. Summary and Recommendations

6.1 Summary

The thermodynamic structure of two case studies is studied in detail and in both cases there is a poor initialisation of the model thermodynamic structure. The modelled inversions are neither strong nor sharp enough and the model is found to be too moist both above the inversion and in the sub-cloud layer. In IOP 1, the modelled boundary layer evolves too slowly causing the modelled inversion to be misplaced in the vertical.

In general the model produces a good simulation of cloud, with cloud amount errors appearing to be case dependant. In IOP 1, there is an overestimate in model cloud amount from 08z onwards leading to an underestimate in 1.5m temperatures. The model cloud base is too low (as a result of the inversion being misplaced) and spurious model cloud is found in the sub-cloud layer as result of a moist bias. In contrast there is an underestimate in model low cloud amount in IOP 2 as a result of too much high cloud in the model.

The turbulent heat and moisture fluxes in one case study were studied in detail and whilst the surface fluxes are generally well modelled, the inversion fluxes seem unrealistically large.

In an attempt to improve the forecast, a test version of the Mesoscale Model was run with 45 levels in the vertical (the operational model has 38 levels), with five of these extra levels in the boundary layer. It was found that the sharpness of the temperature and humidity profile at the inversion was sometimes increased, leading to an increase in the amount of low cloud.

6.2 Recommendations

1. Carry out further case studies (IOP's).

2. Test Mesoscale Model performance at version 5.2 (New Dynamics).

3. Test the sensitivity of the extra vertical resolution run to the profile of critical relative humidity/placing of levels etc.

4. Test the combined effect of assimilation and increased vertical resolution.

5. Investigate moisture initialisation

6. Investigate possible overestimate of model entrainment fluxes/intermittent nature.

7. Cardington to review the quality of data from the radiometers/ use pyrgeometers.

8. Ensure the balloon is in a fit state to fly with a full set of probes (flux measurements).

9. For NWP studies, five probes should be placed between the surface and 0.75 times the height of the boundary layer top

10. Comparison with other data sources and for a longer timeseries of cloud imagery (e.g. Chilbolton cloud radar, BSRN* data, NIMROD analyses).

*Baseline Surface Radiation network

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Appendix A

Cardington sonde, balloon and surface site data with corresponding Mesoscale Model diagnostics. Grey shading denotes data presented in this report.

Cardington Sonde/Balloon data	Mesoscale model diagnostics
Sonde/Balloon temperature, T	Temperature on model levels (38)
Sonde dewpoint temperature, Td	Td (computed)
Balloon probe heat fluxes	Surface & boundary layer heat fluxes
Balloon probe moisture fluxes	Surface & boundary layer moisture fluxes
Balloon probe theta	Theta on model levels
Balloon probe pressure	Pressure on model levels (computed)
Balloon probe relative humidity, RH	R.H humidity on model levels (computed)
Balloon probe specific humidity, q	Specific humidity on model levels
Balloon probe zonal and meridional wind	u-wind and v-wind on model levels
Balloon probe vertical velocity, w	w on model levels (computed)
Cardington surface site data	**Mesoscale model diagnostics**
Laser cloud base recorder	Cloud amount in a layer (on model levels)
Manual cloud observations	Cloud fraction (low, medium, high, total)
Solarimeter (up-facing, down-facing)	SW radiation (downwelling, upwelling)
Schulz radiometer (upper, lower domes)	Total radiation (downwelling, upwelling)
Schulz (upper, lower) - Solarimeter(up,dn)	LW radiation (downwelling, upwelling)
Temperature at 1.2m	1.5m temperature
Surface heat and moisture fluxes	First model half level heat, moisture fluxes
Pressure at station level (29m)	Mean Sea Level Pressure
Humicap relative humidity sensor at 1.2m	1.5m relative humidity
Mitchell specific humidity sensor	1.5m specific humidity
Belfort visibility sensor	1.5m visibility
Sonic wind speed at 10m	10m wind speed
Zonal and Meridional wind	10m u-wind and v-wind

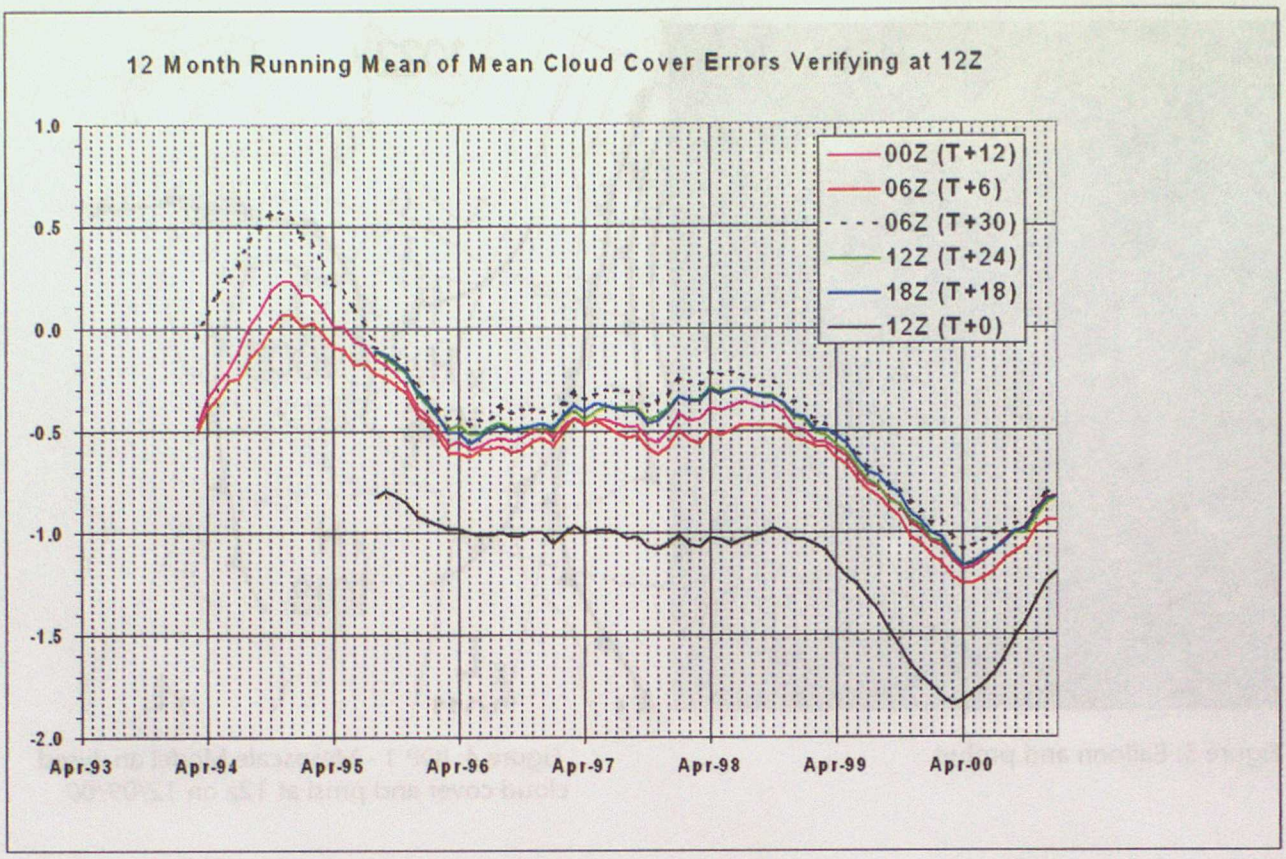

Figure 1: 12 month running mean of the 12z cloud cover bias meaned over 42 U.K stations

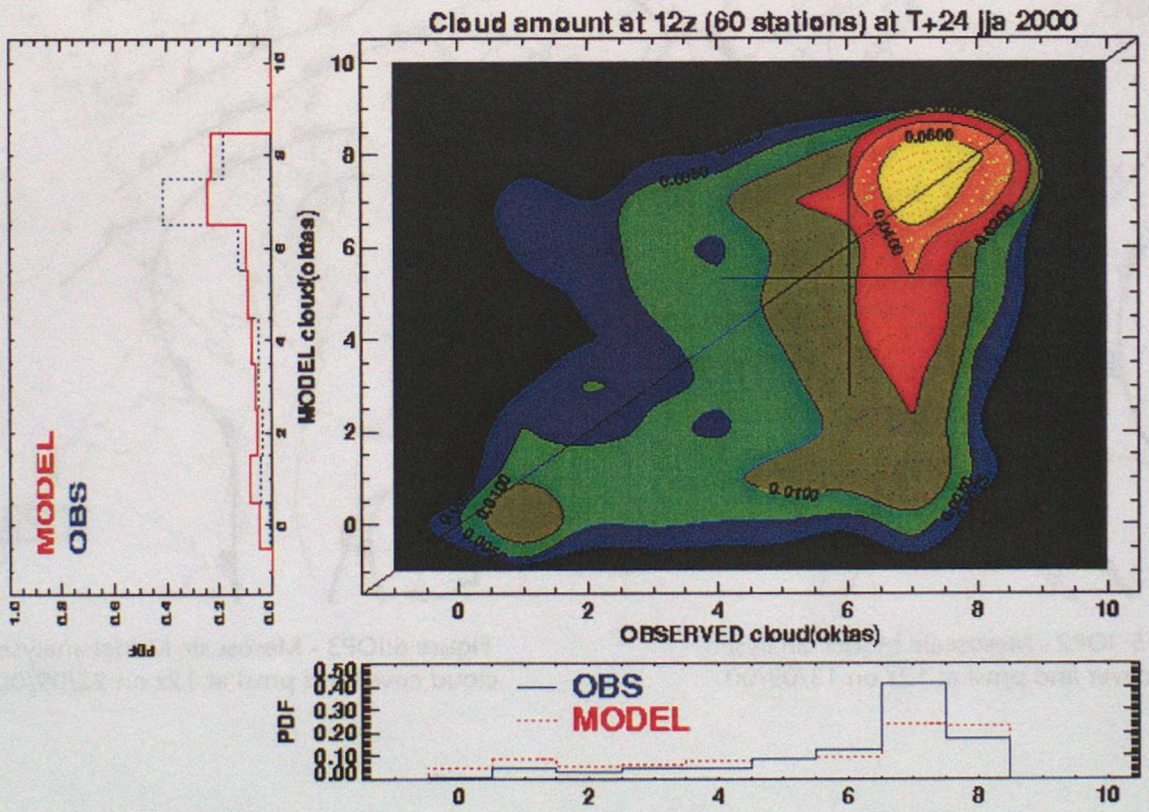

Figure 2: Joint distribution of errors for 12z cloud cover at T+24 for JJA 2000. Colour filled contours show relative frequencies. Two side panels show marginal distributions p(f) and p(o).

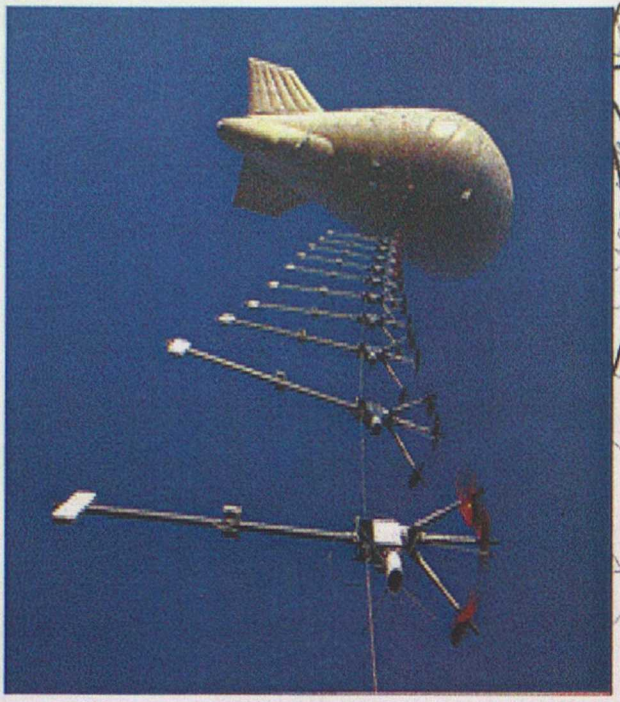

Figure 3: Balloon and probes

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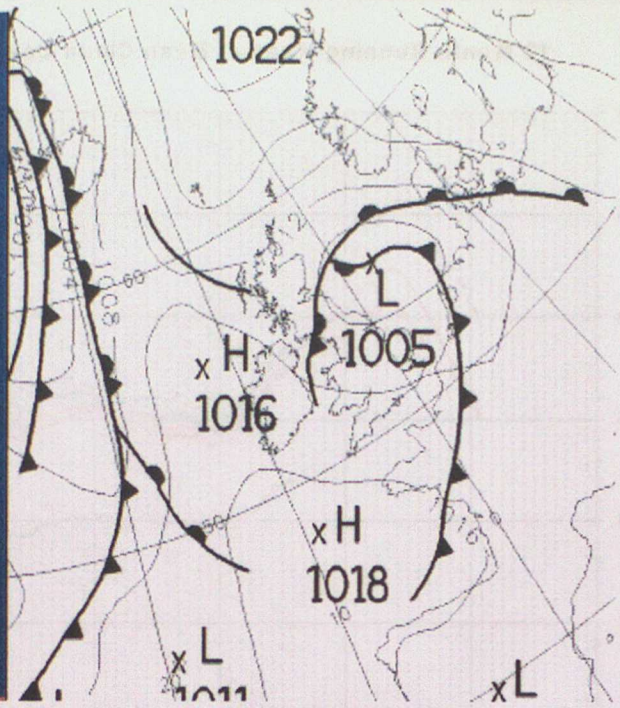


Figure 4: IOP 1 - Mesoscale Model analysed cloud cover and pmsl at 12z on 12/09/00

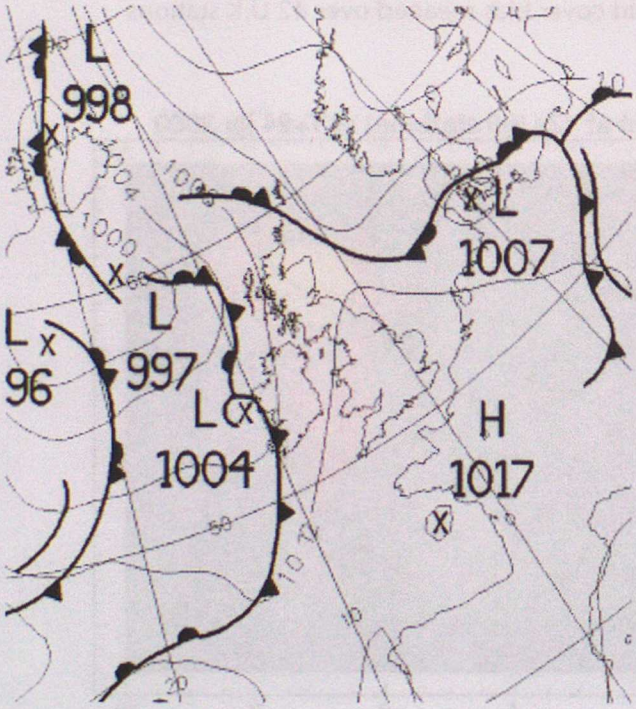


Figure 5: IOP2 - Mesoscale Model analysed cloud cover and pmsl at 12z on 13/09/00

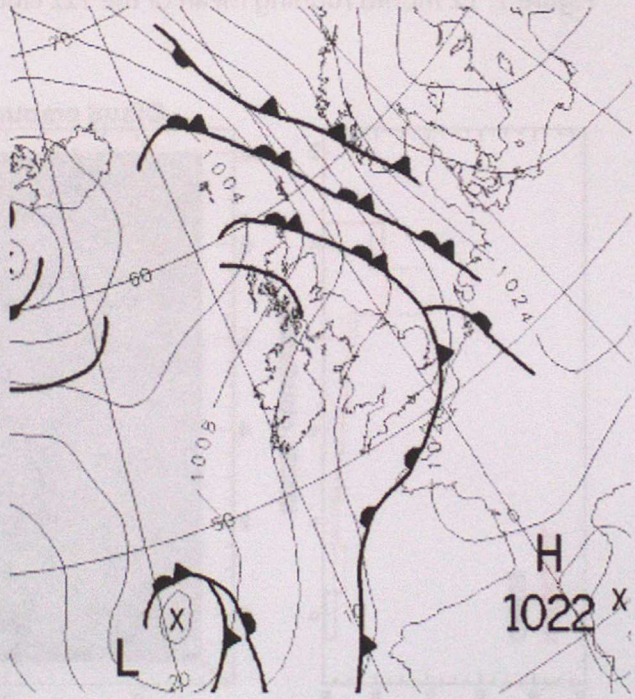
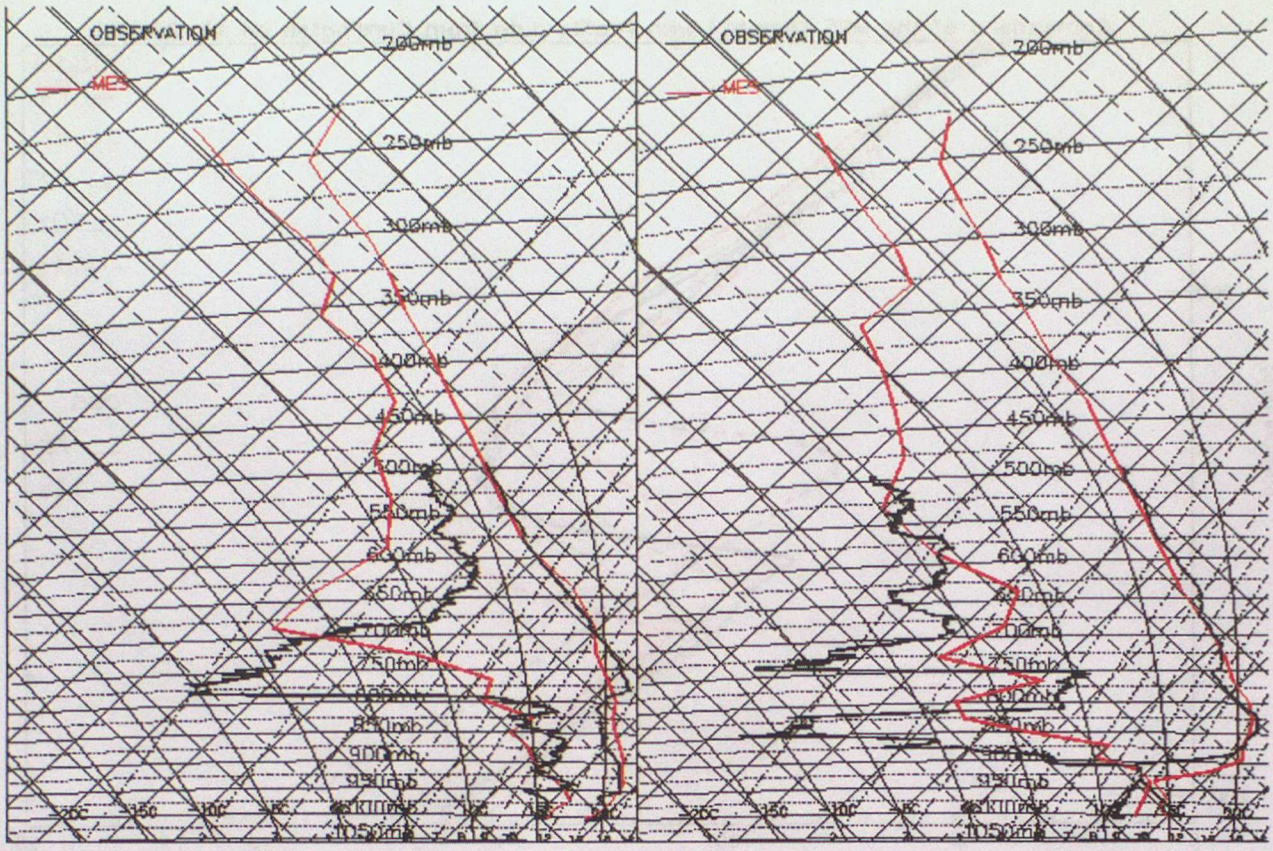


Figure 6:IOP3 - Mesoscale Model analysed cloud cover and pmsl at 12z on 22/09/00

(a) IOP1 - 00z

(b) IOP1 - 07z

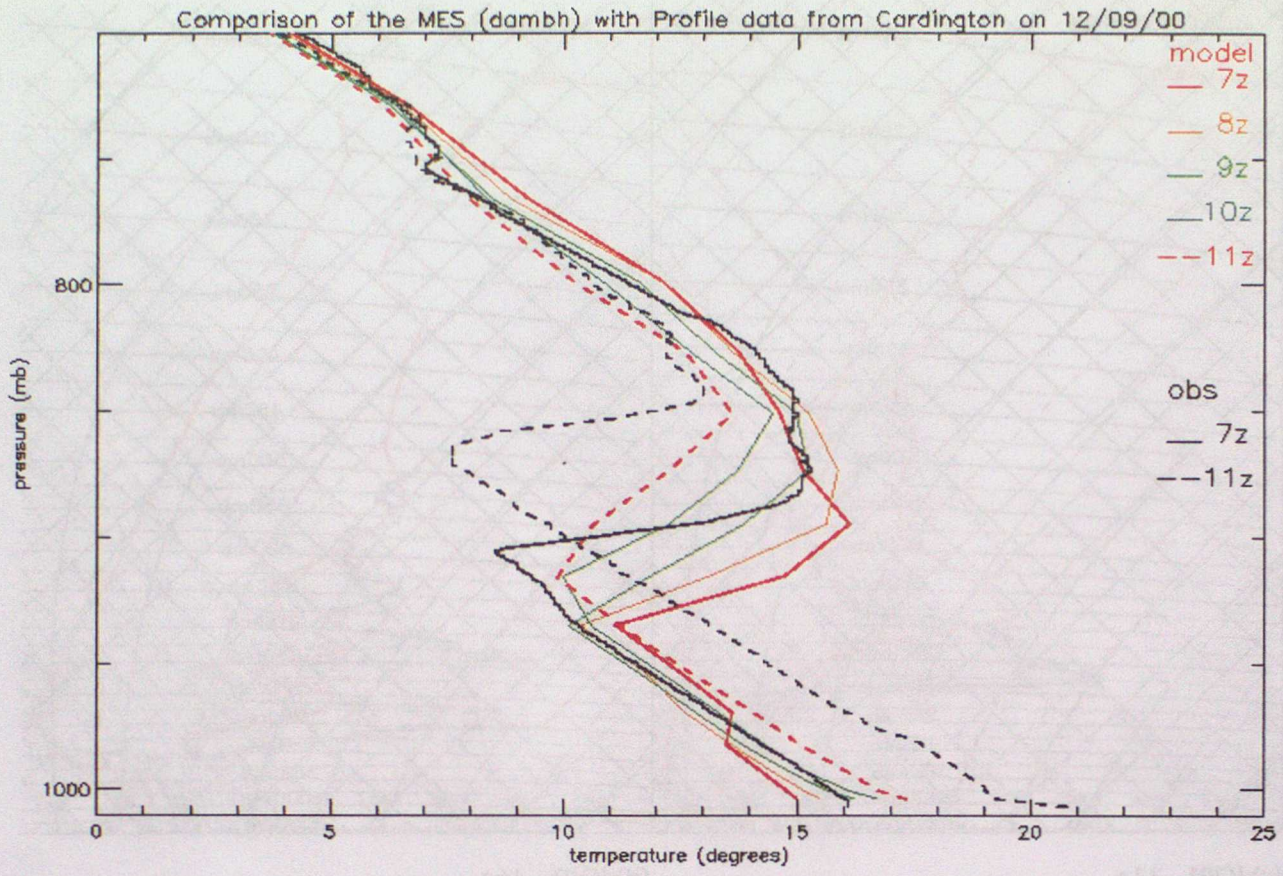


(c) IOP1 - 11z

(d) IOP1 - 15z

Figure 7: IOP 1 - Tephigrams showing ascents at (a) 00z, (b) 07z, (c) 11z and (d) 15z on the 12/09/00 with the Mesoscale Model forecast (T+0, T+7, T+11, T+15) overplotted.

(a) morning



(b) afternoon

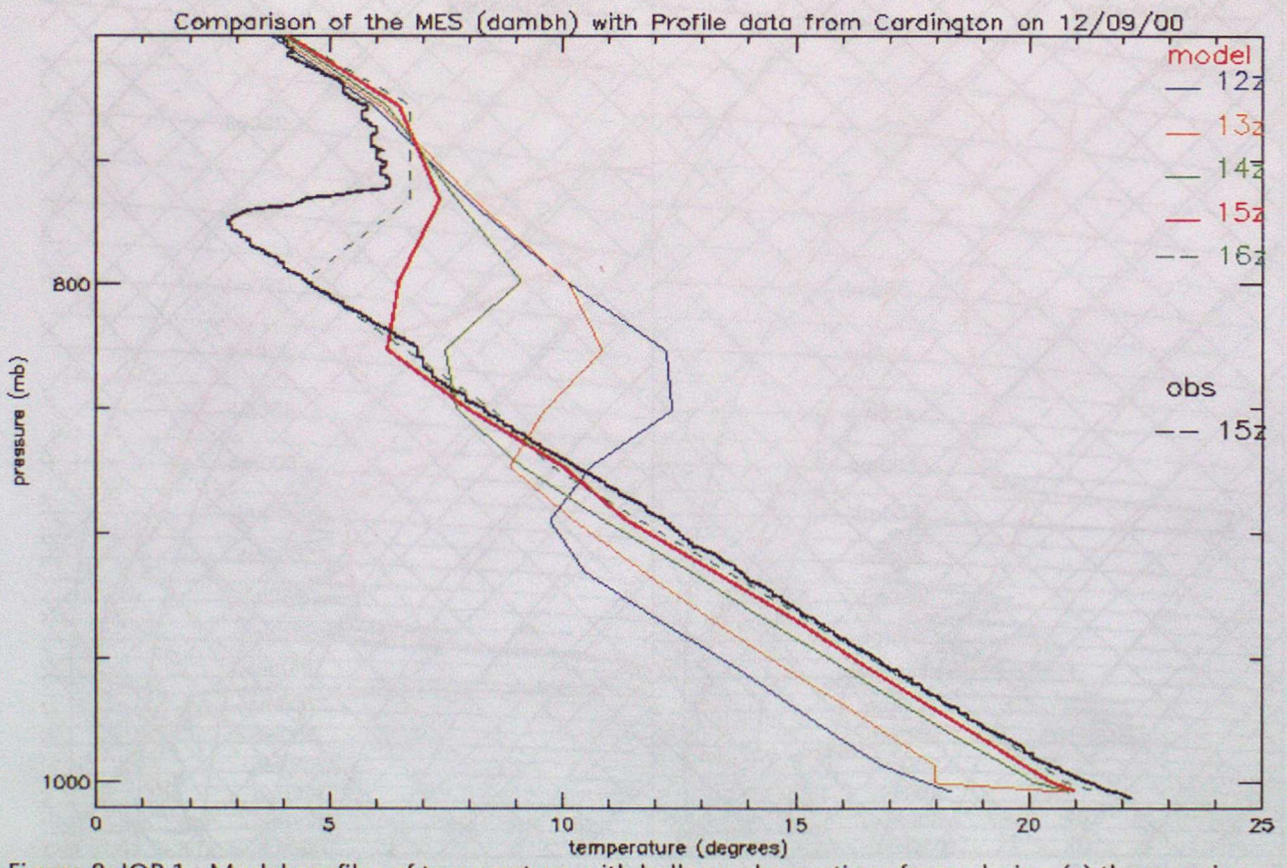
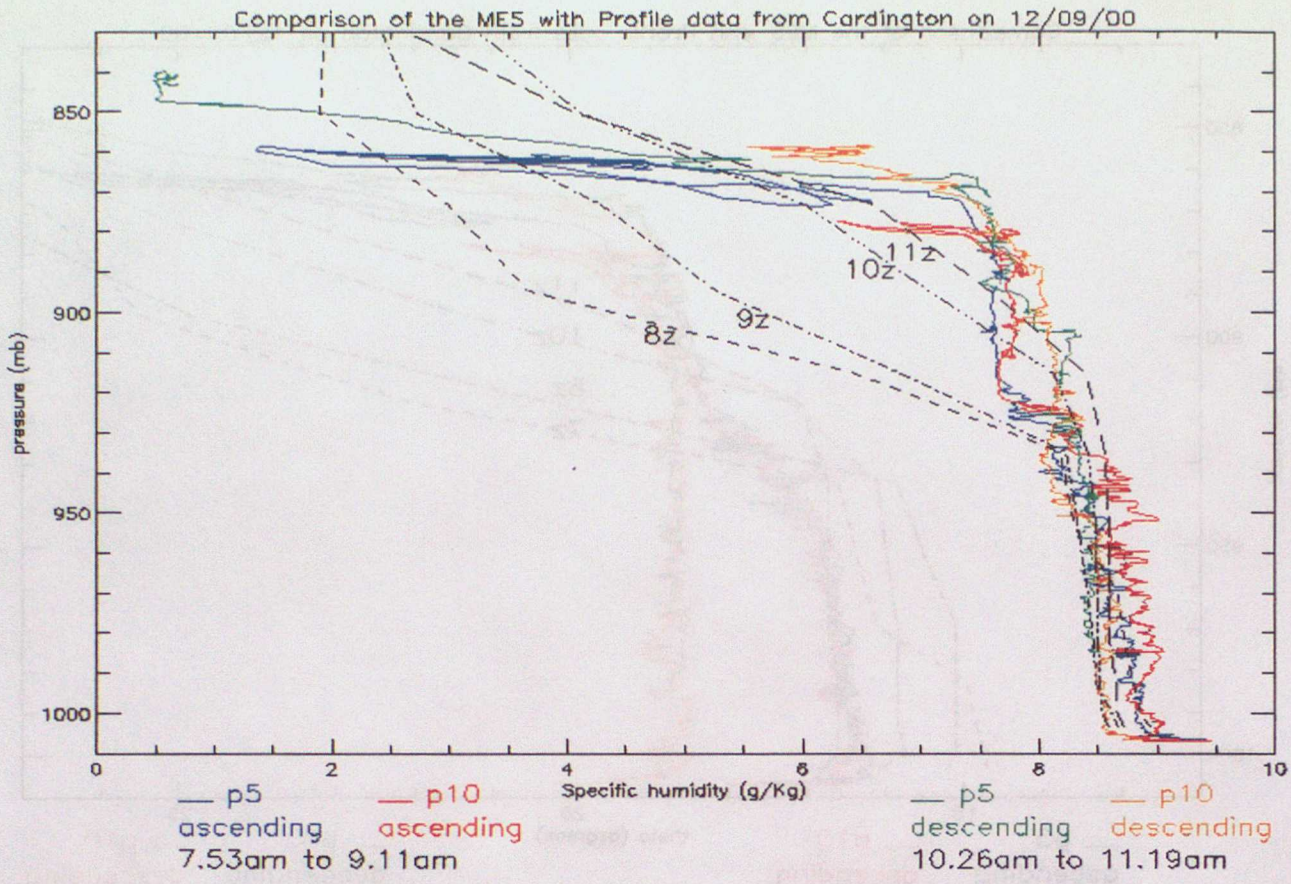


Figure 8: IOP 1 - Model profiles of temperature with balloon observations from during (a) the morning and (b) the afternoon of 12/09/00.

(a) morning



(b) afternoon

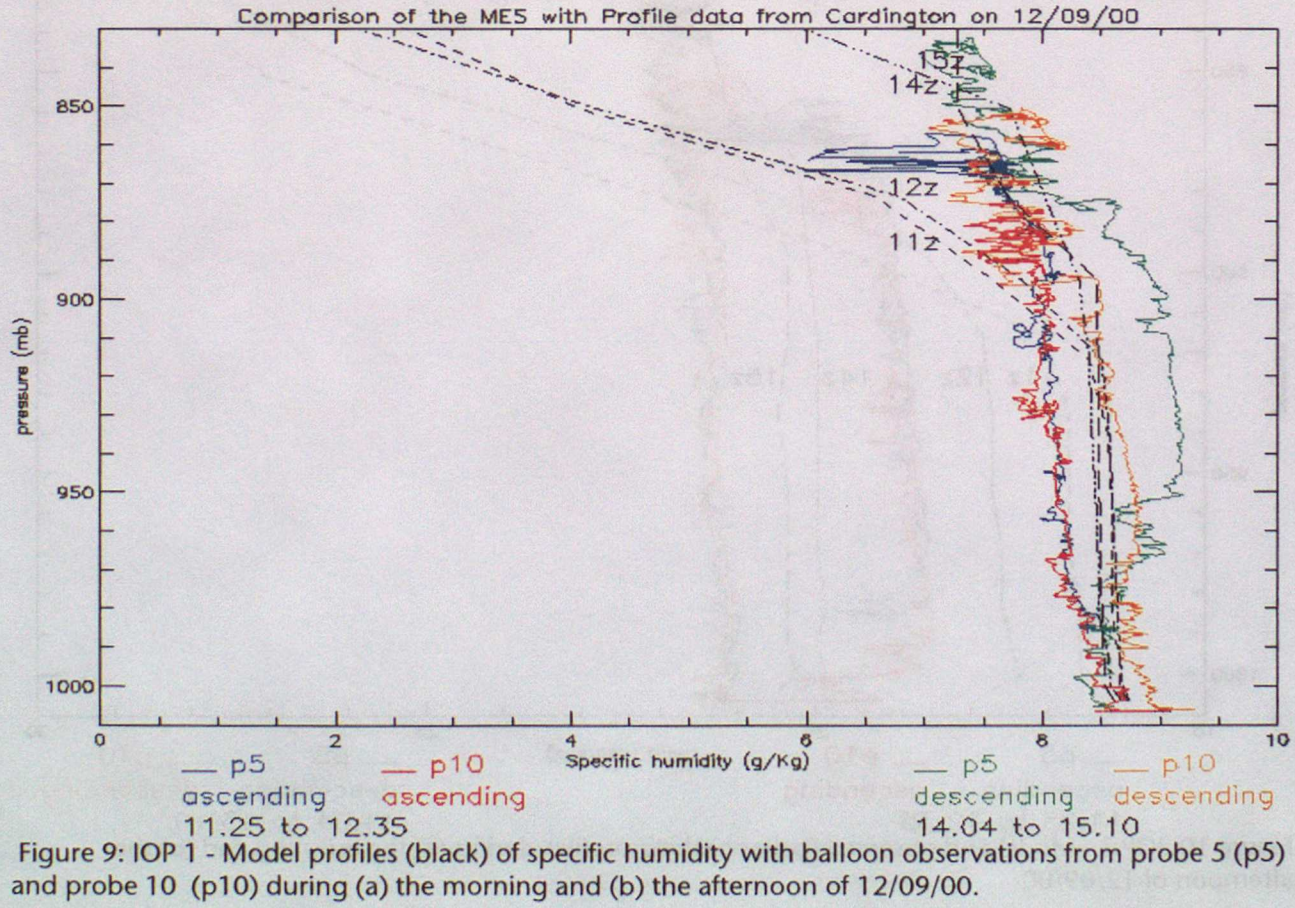
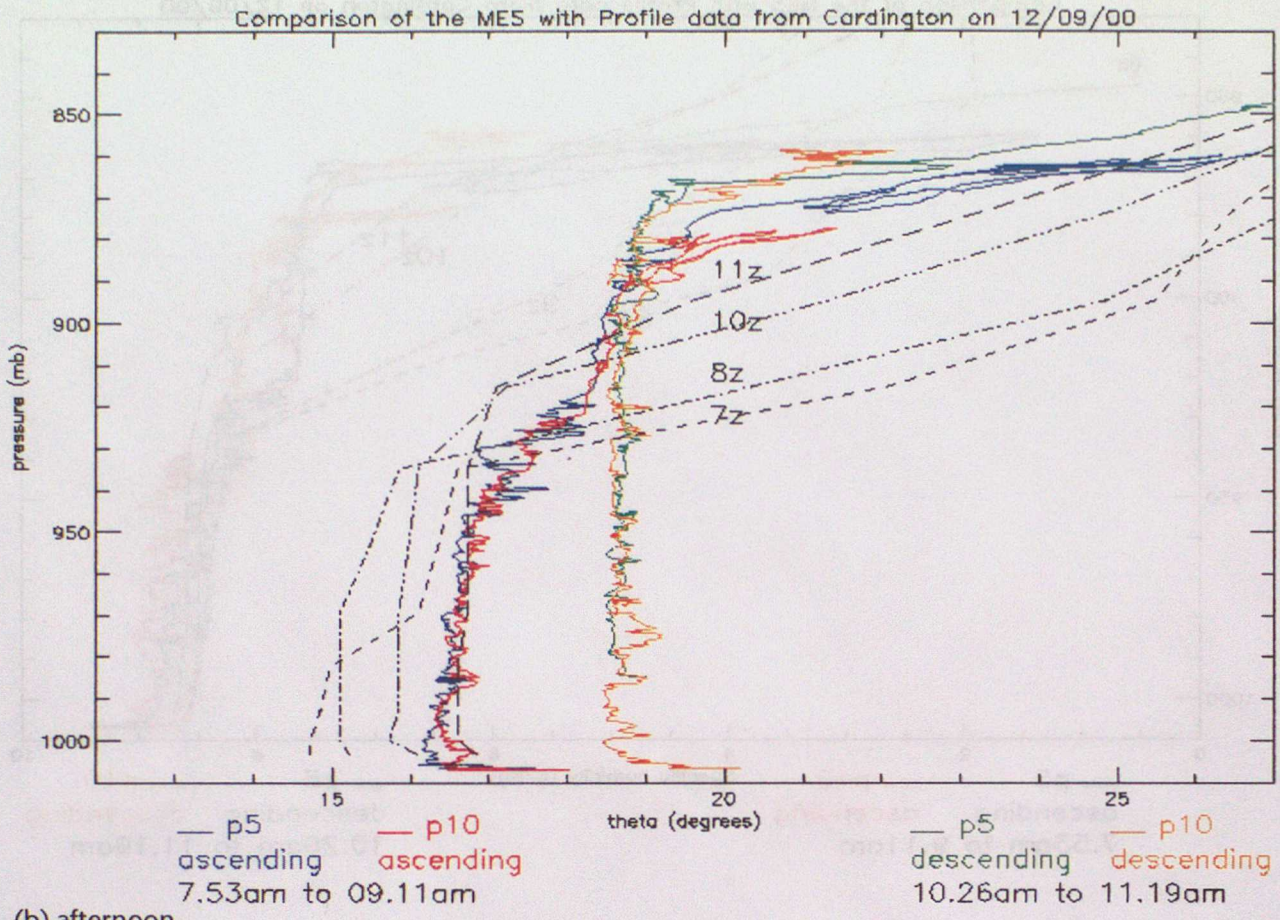


Figure 9: IOP 1 - Model profiles (black) of specific humidity with balloon observations from probe 5 (p5) and probe 10 (p10) during (a) the morning and (b) the afternoon of 12/09/00.

(a) morning



(b) afternoon

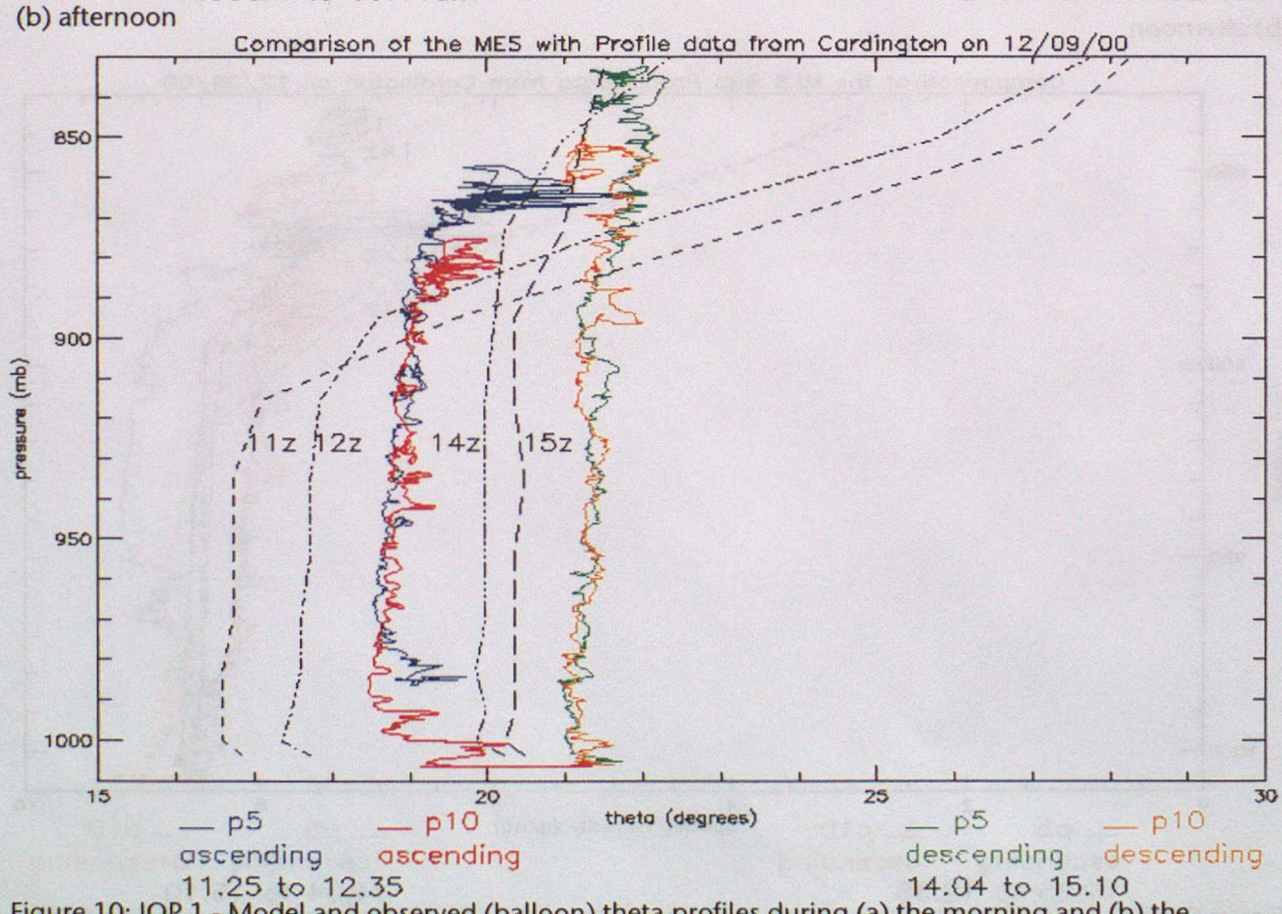


Figure 10: IOP 1 - Model and observed (balloon) theta profiles during (a) the morning and (b) the afternoon of 12/09/00

(a) IOP2 - 00z

(b) IOP2 - 07z

(c) IOP2 - 11z

(d) IOP2 - 15z

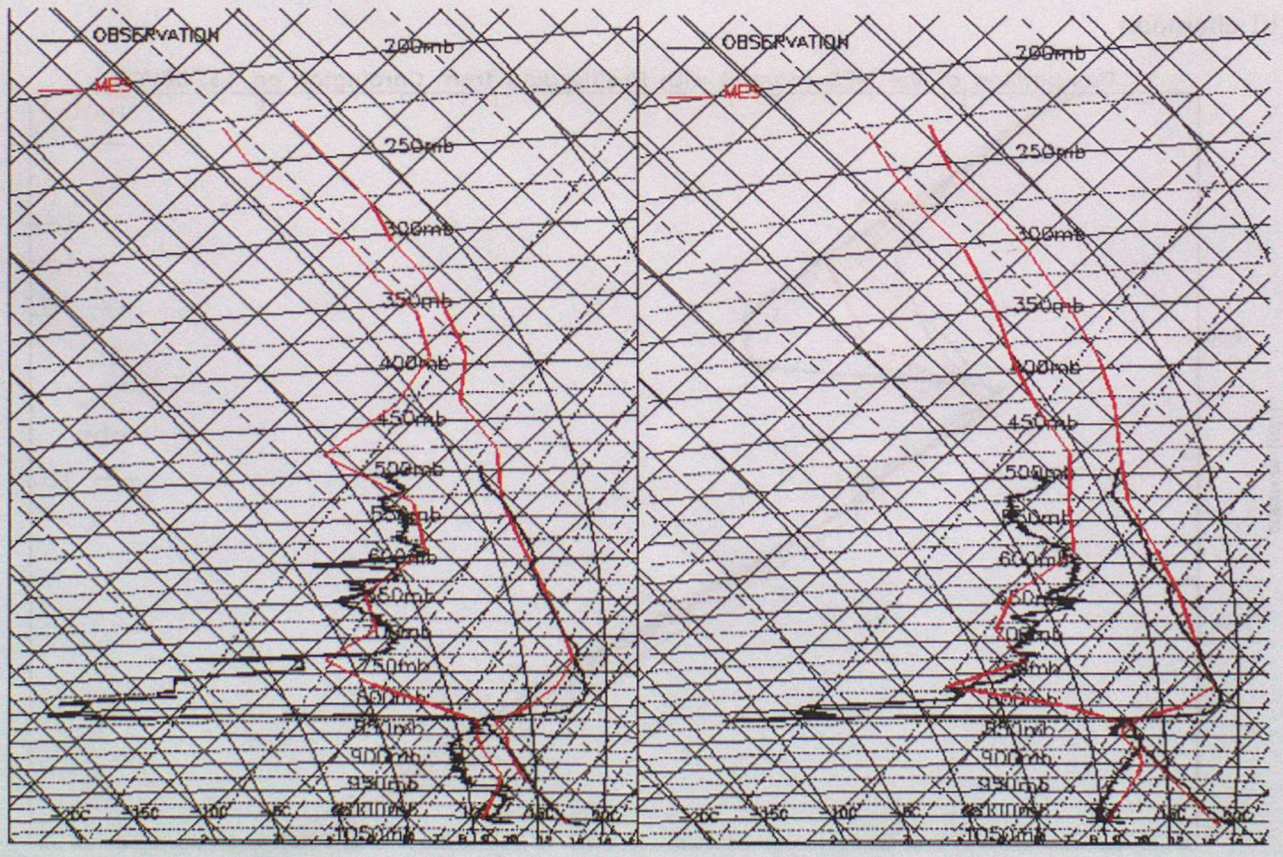
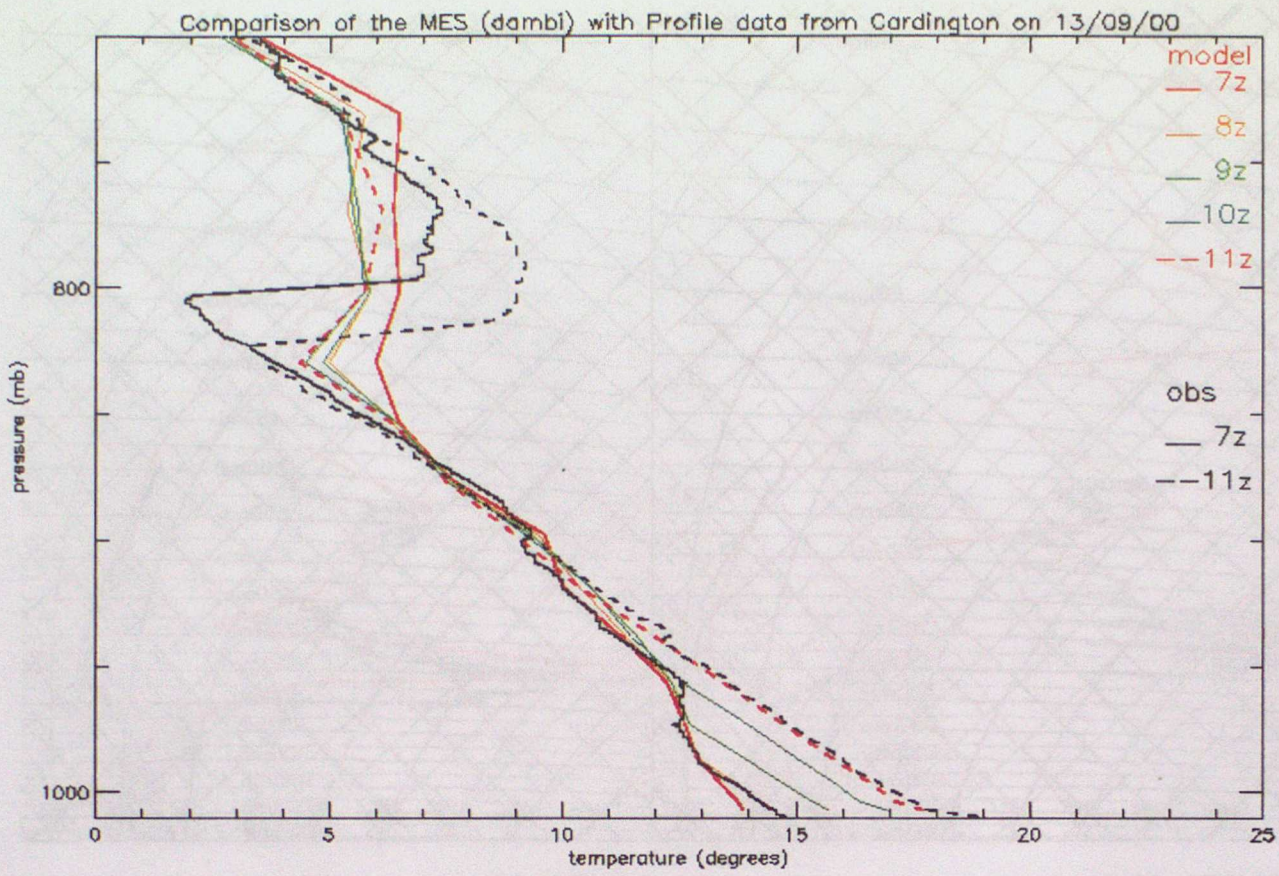


Figure 11: IOP2 - Tephigrams showing ascents at (a) 00z, (b) 07z, (c)11z and (d) 15z on the 13/09/00 with the Mesoscale model (T+0, T+7, T+11 and T+15) overplotted.

(a) morning



(b) afternoon

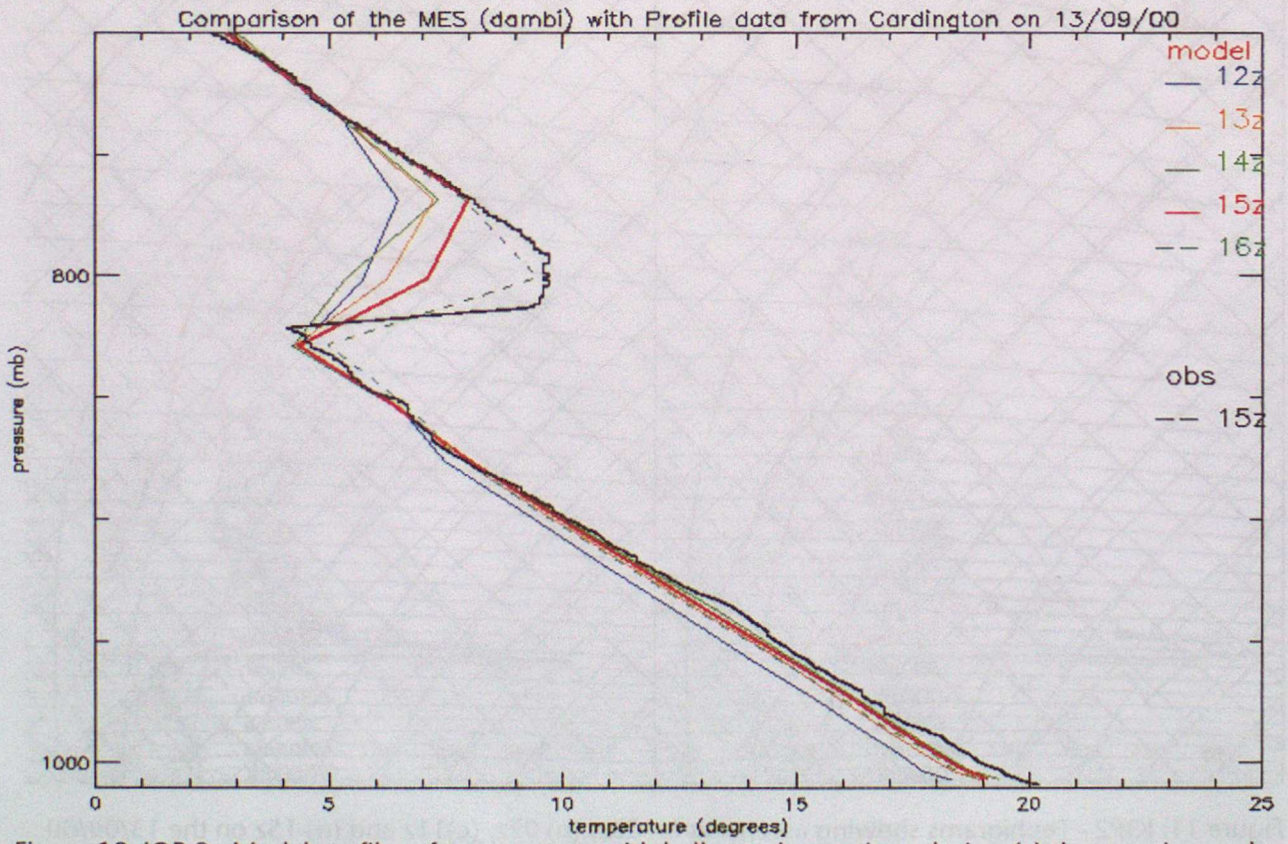
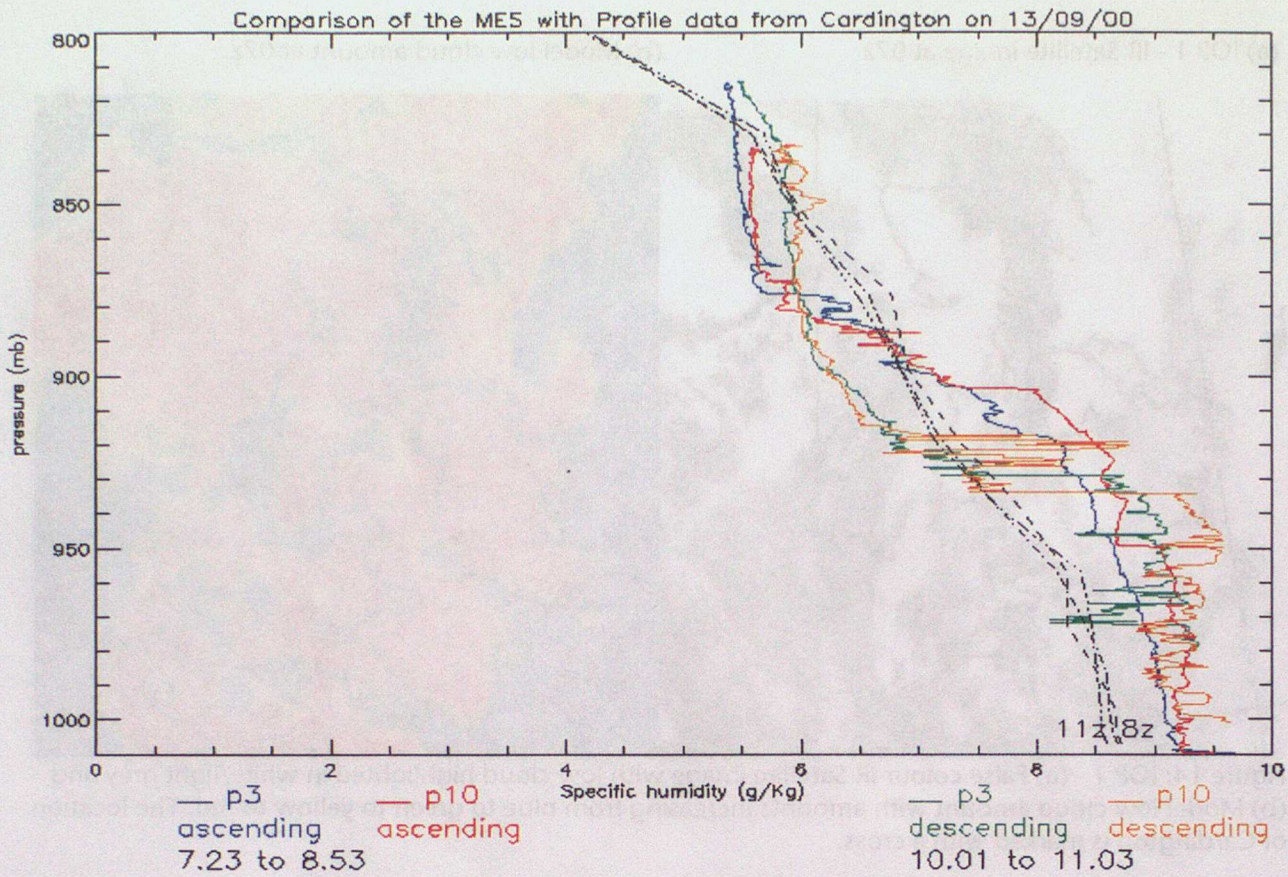


Figure 12: IOP 2 - Model profiles of temperature with balloon observations during (a) the morning and (b) the afternoon of 13/09/00.

(a) morning



(b) afternoon

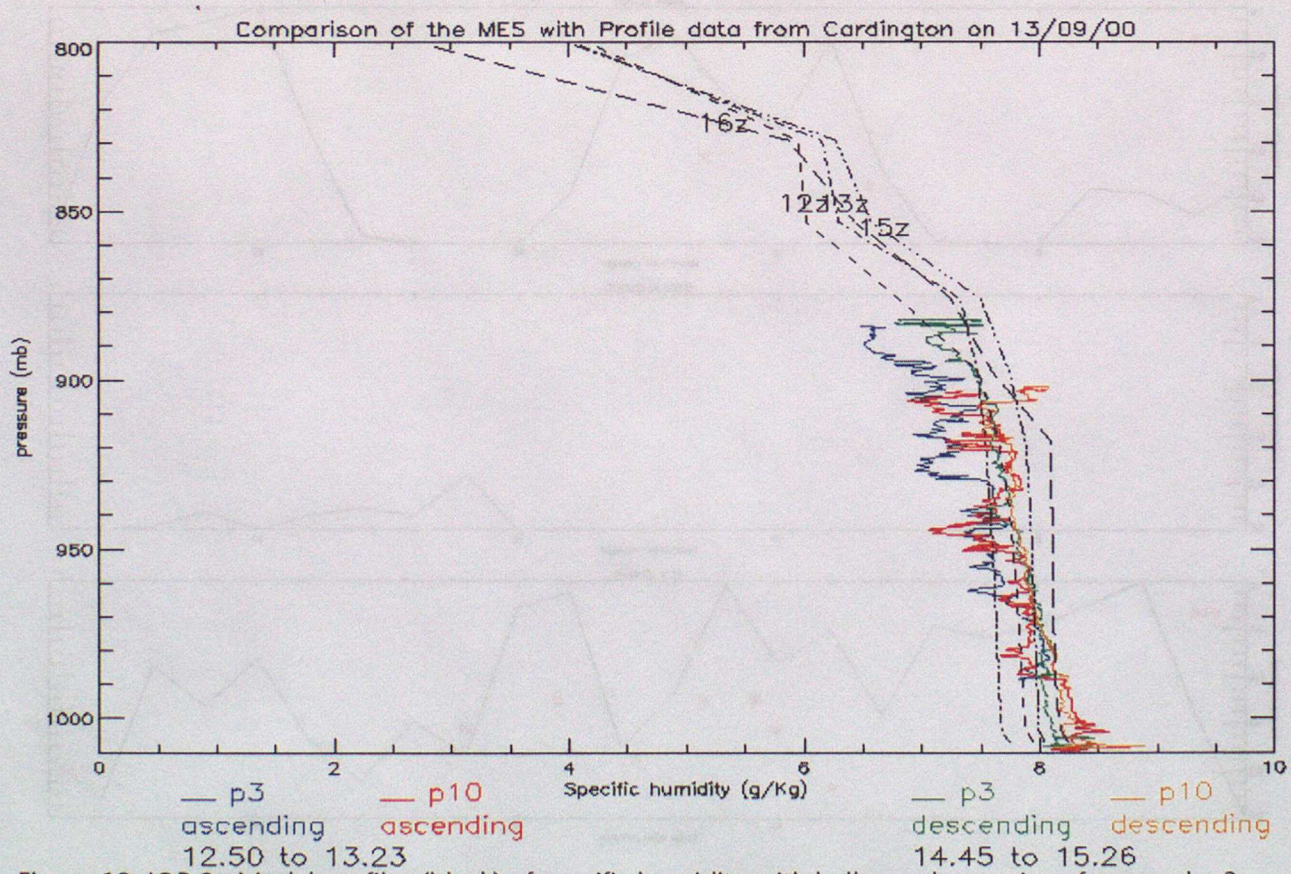


Figure 13: IOP 2 - Model profiles (black) of specific humidity with balloon observations from probe 3 (p3) and probe 10 (p10) during (a) the morning and (b) the afternoon of 13/09/00.

(a) IOP 1 - IR Satellite image at 07z

(b) Model low cloud amount at 07z

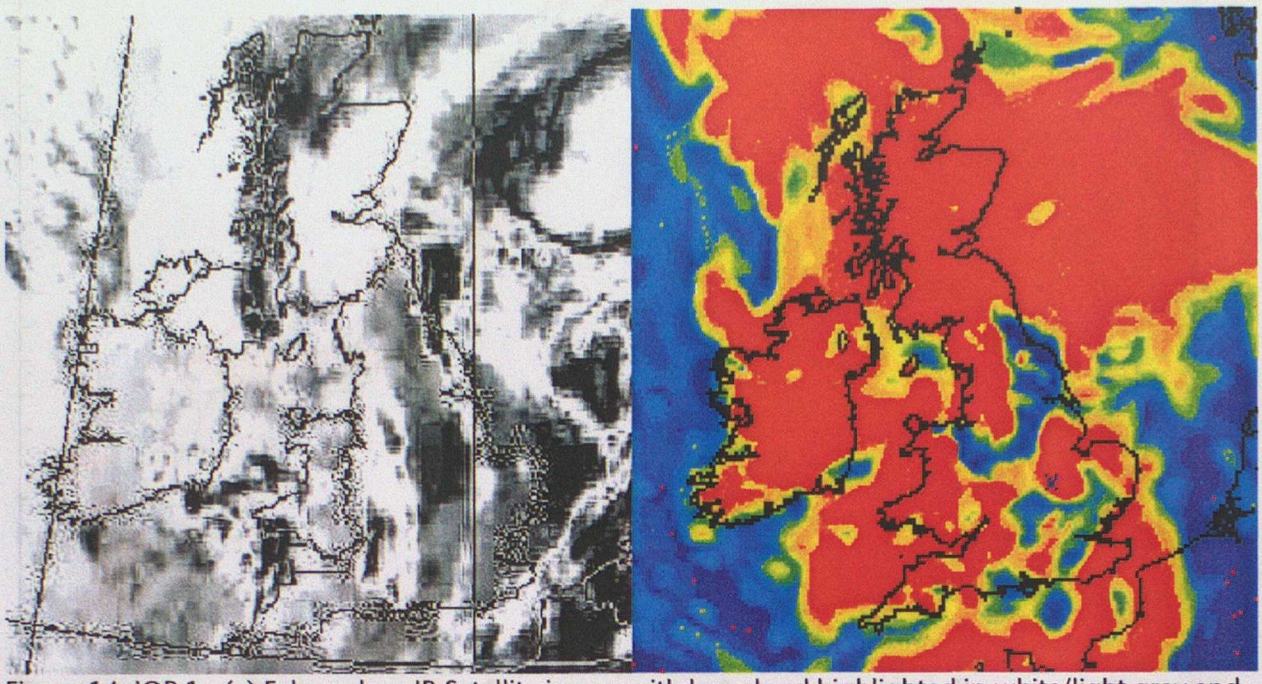


Figure 14: IOP 1 - (a) False colour IR Satellite image with low cloud highlighted in white/light grey and (b) Model low cloud amount with amounts increasing from blue to green to yellow to red. The location of Cardington is marked with a cross.

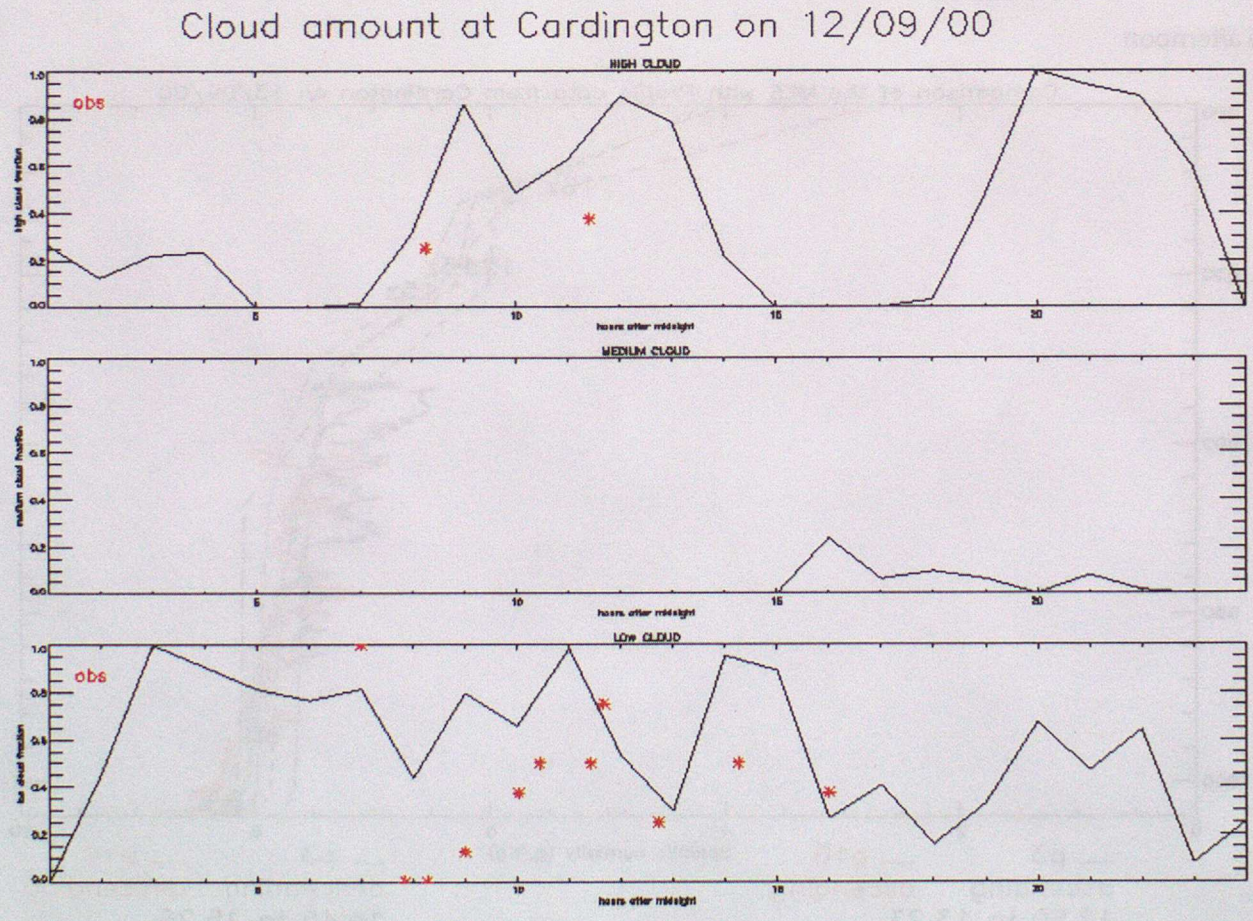


Figure 15: IOP 1 - Model high, medium and low cloud amounts and observations on 12/09/00

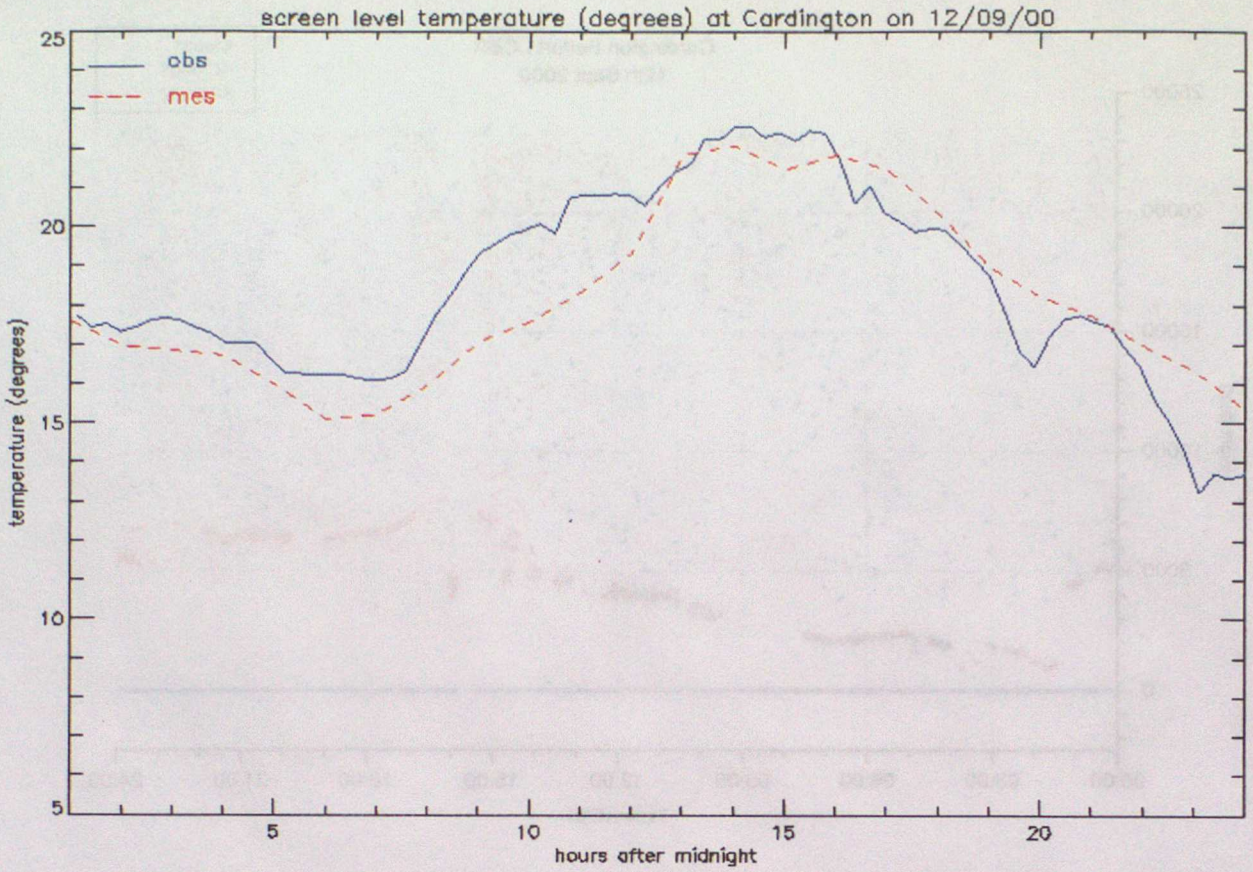


Figure 16: IOP 1 - Model screen level temperature and surface observations on 12/09/00

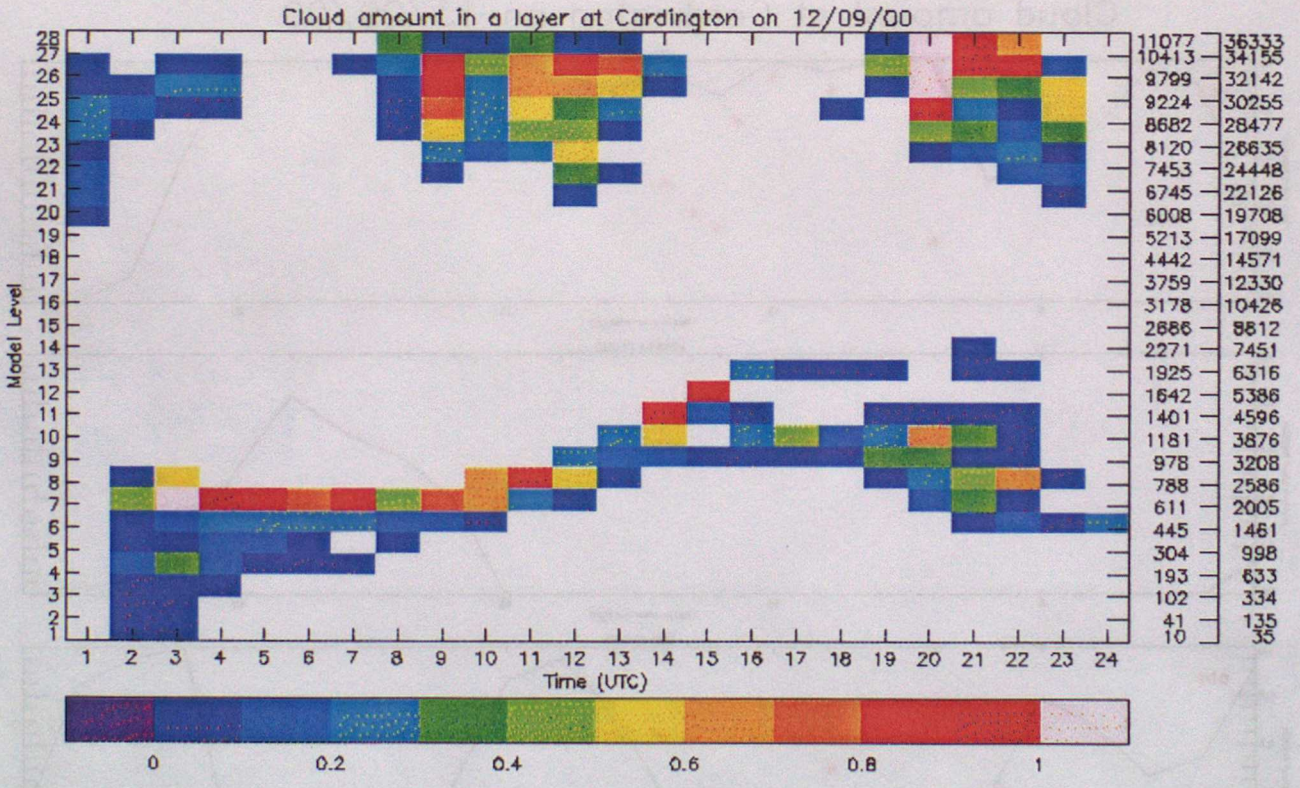


Figure17: IOP 1 - Model cloud amount in a layer on 12/09/00 (heights in metres and feet)

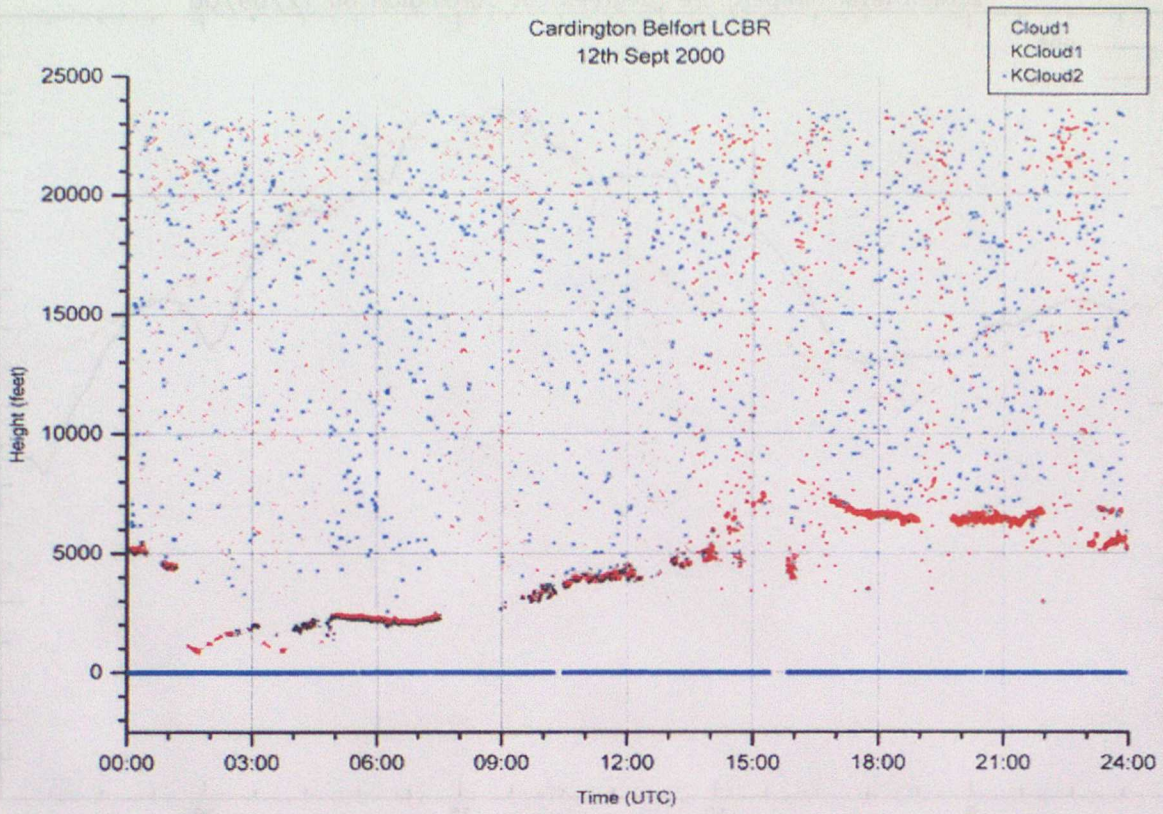


Figure18: IOP 1 - Observations from the laser cloud base recorder at Cardington on 12/09/00

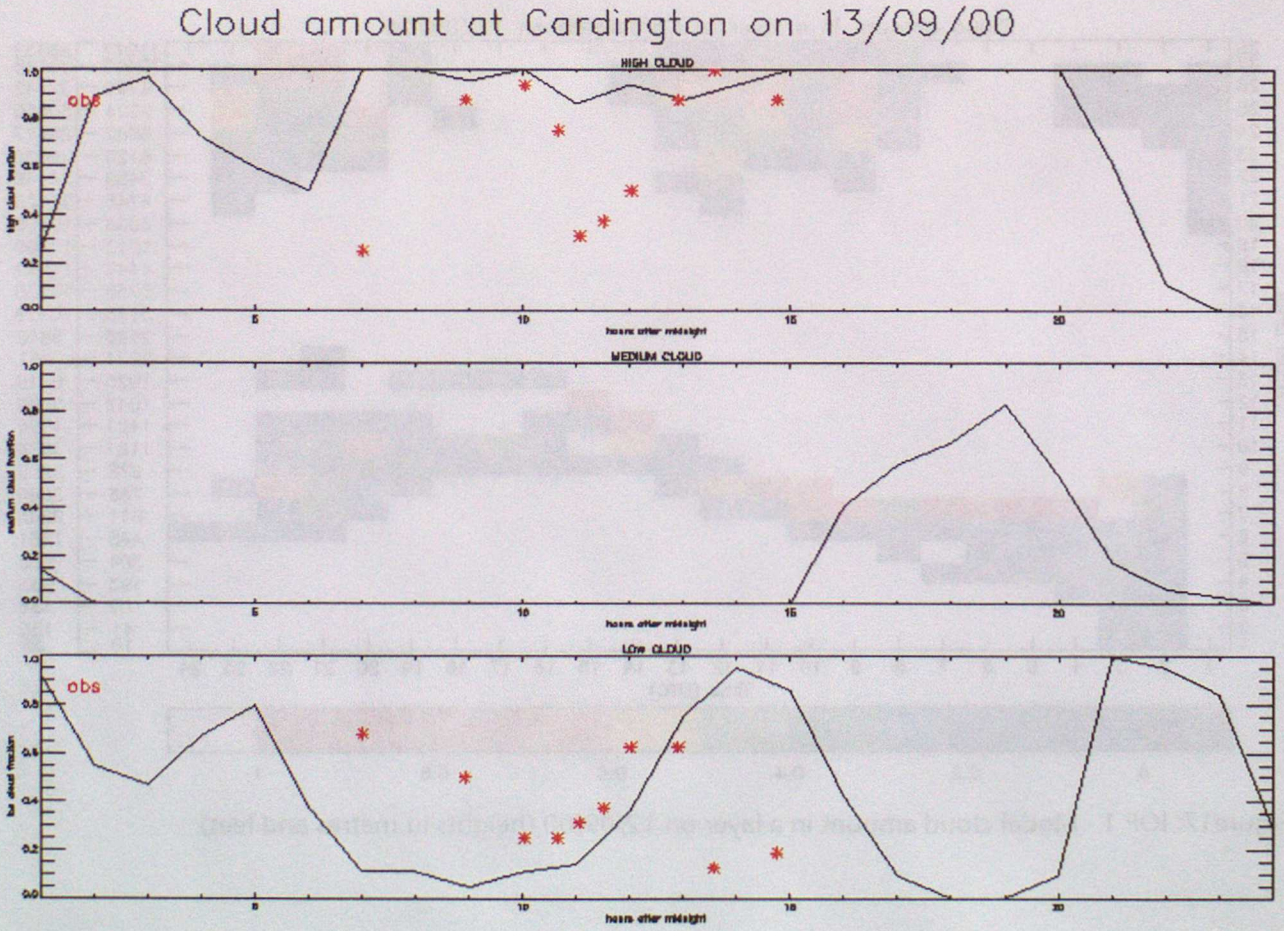


Figure 19: IOP 2 - Model high, medium and low cloud amounts and observations on 13/09/00

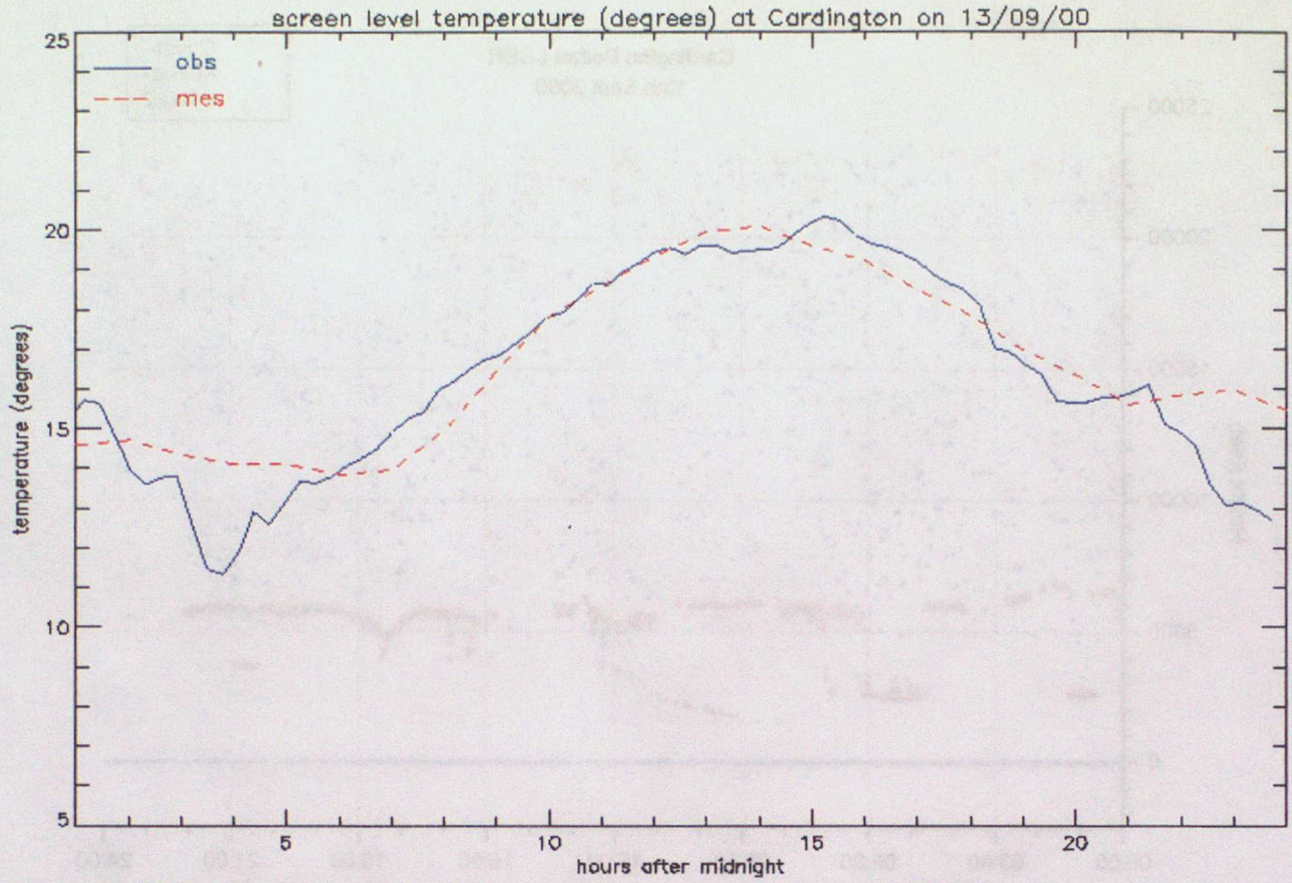


Figure 20: IOP 2 - Model screen level temperature and observations on13/09/00

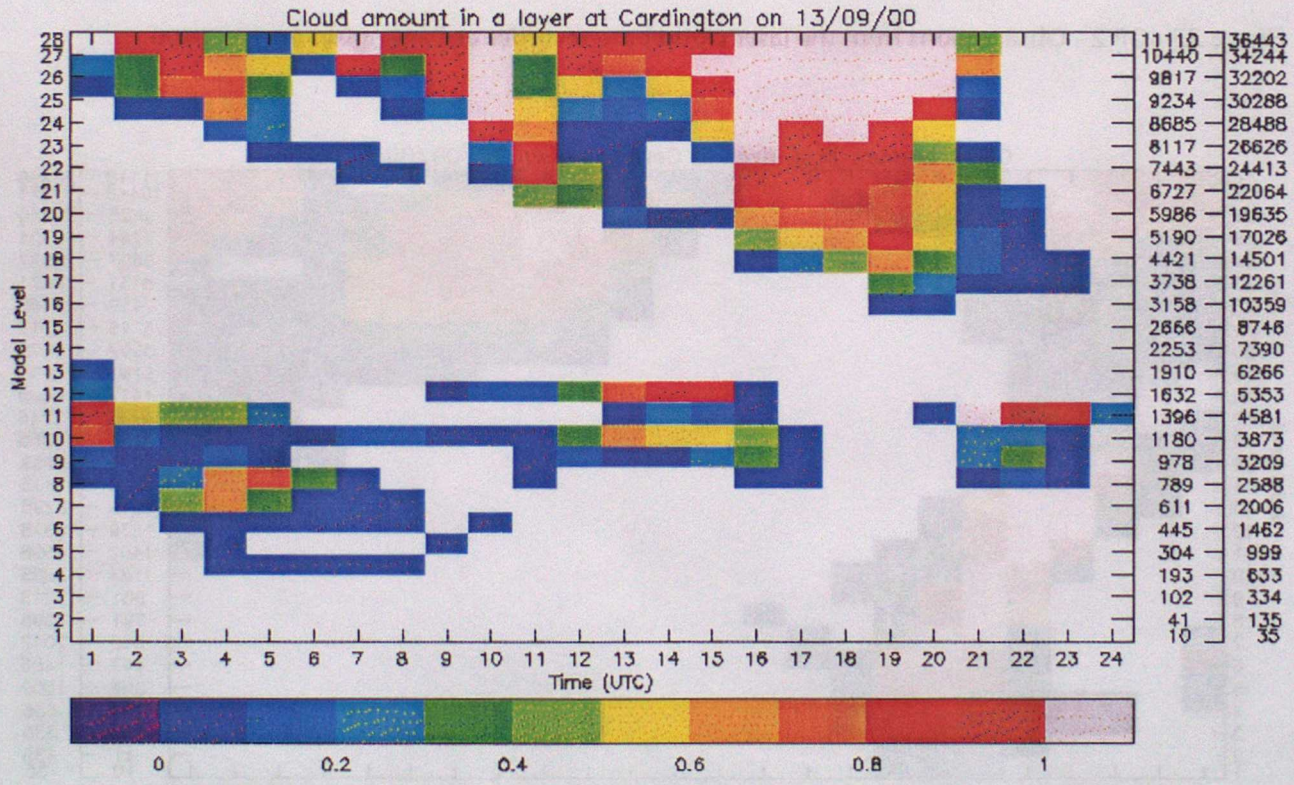


Figure 21: IOP 2 - Model cloud amount in a layer on 13/09/00 (heights in metres and feet)

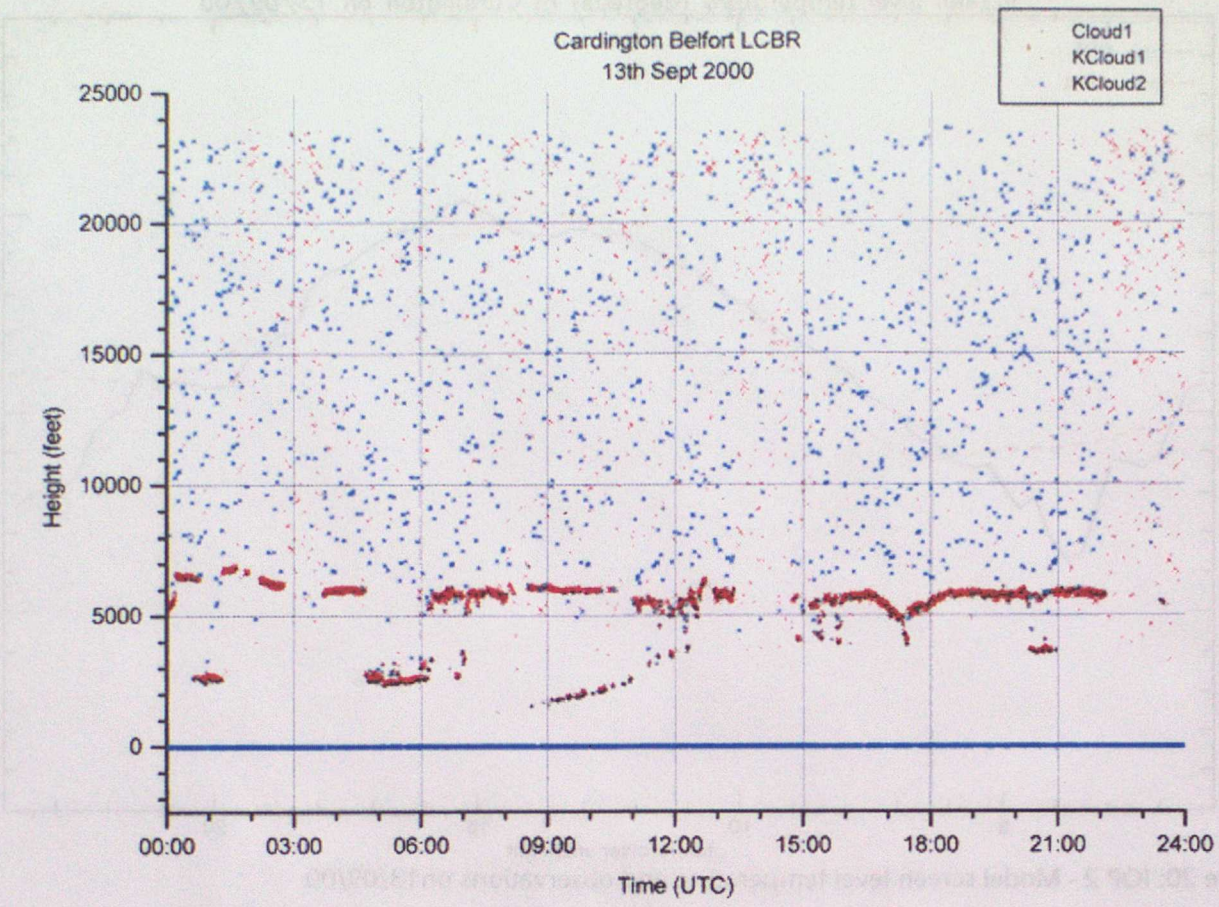


Figure 22: IOP 2 - Observations from the laser cloud base recorder at Cardington on 13/09/00

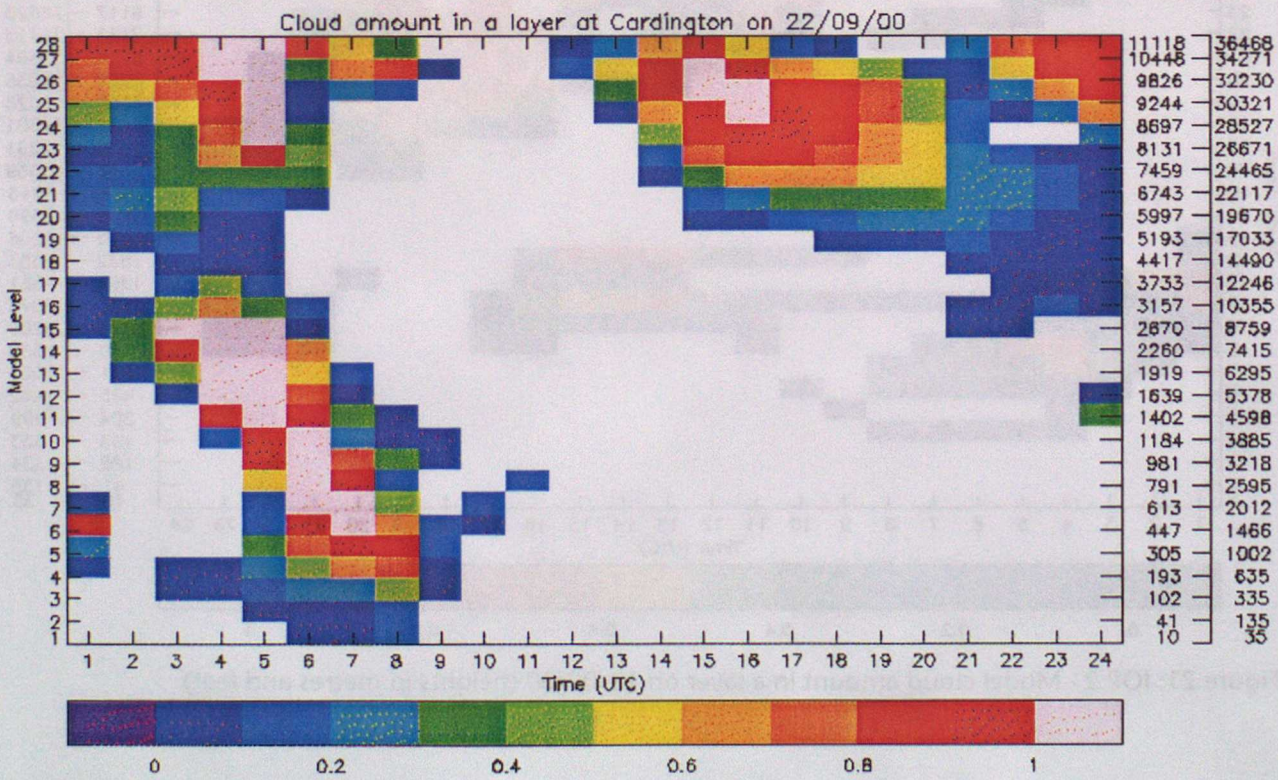


Figure 23: IOP 3 - Model cloud amount in a layer on 22/09/00 (heights in metres and feet)

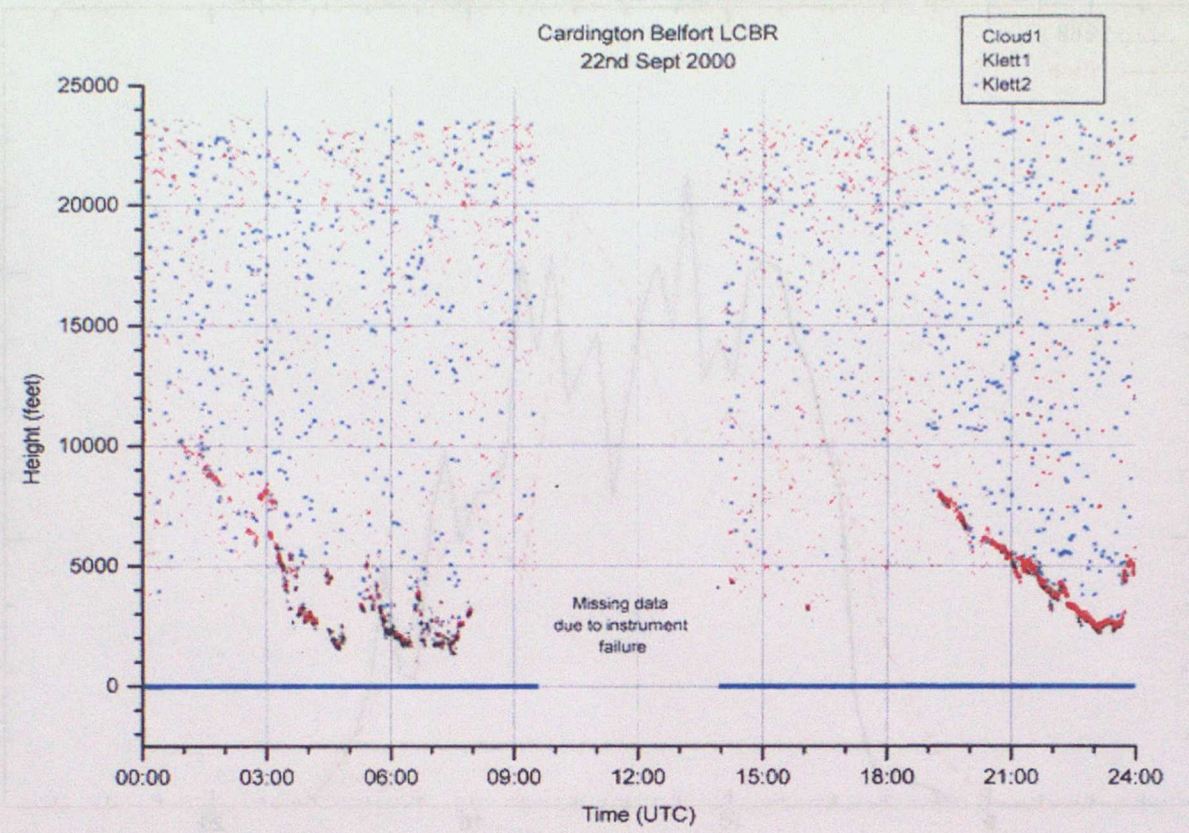


Figure 24: IOP 3 - Observations from the laser cloud base recorder at Cardington on 22/09/00

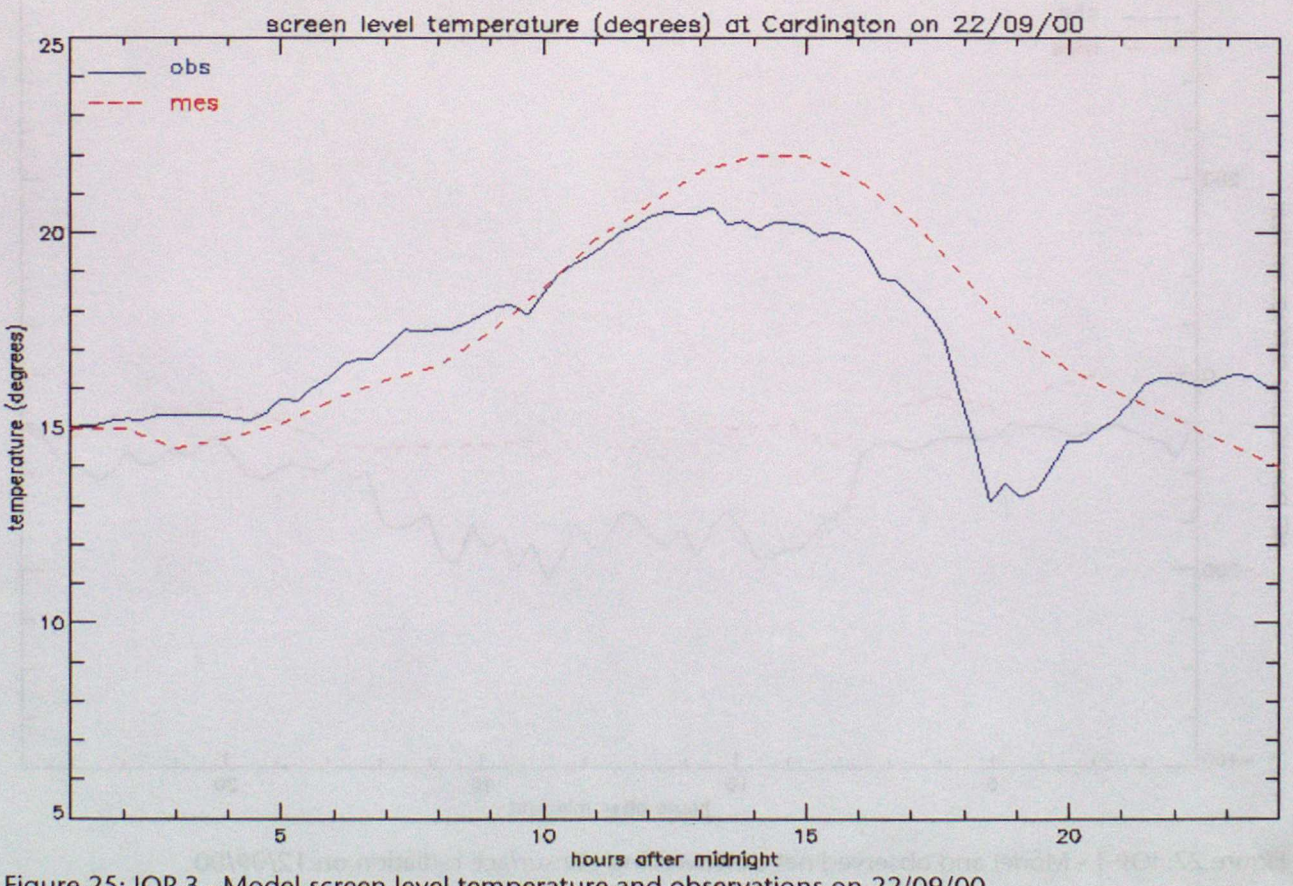


Figure 25: IOP 3 - Model screen level temperature and observations on 22/09/00

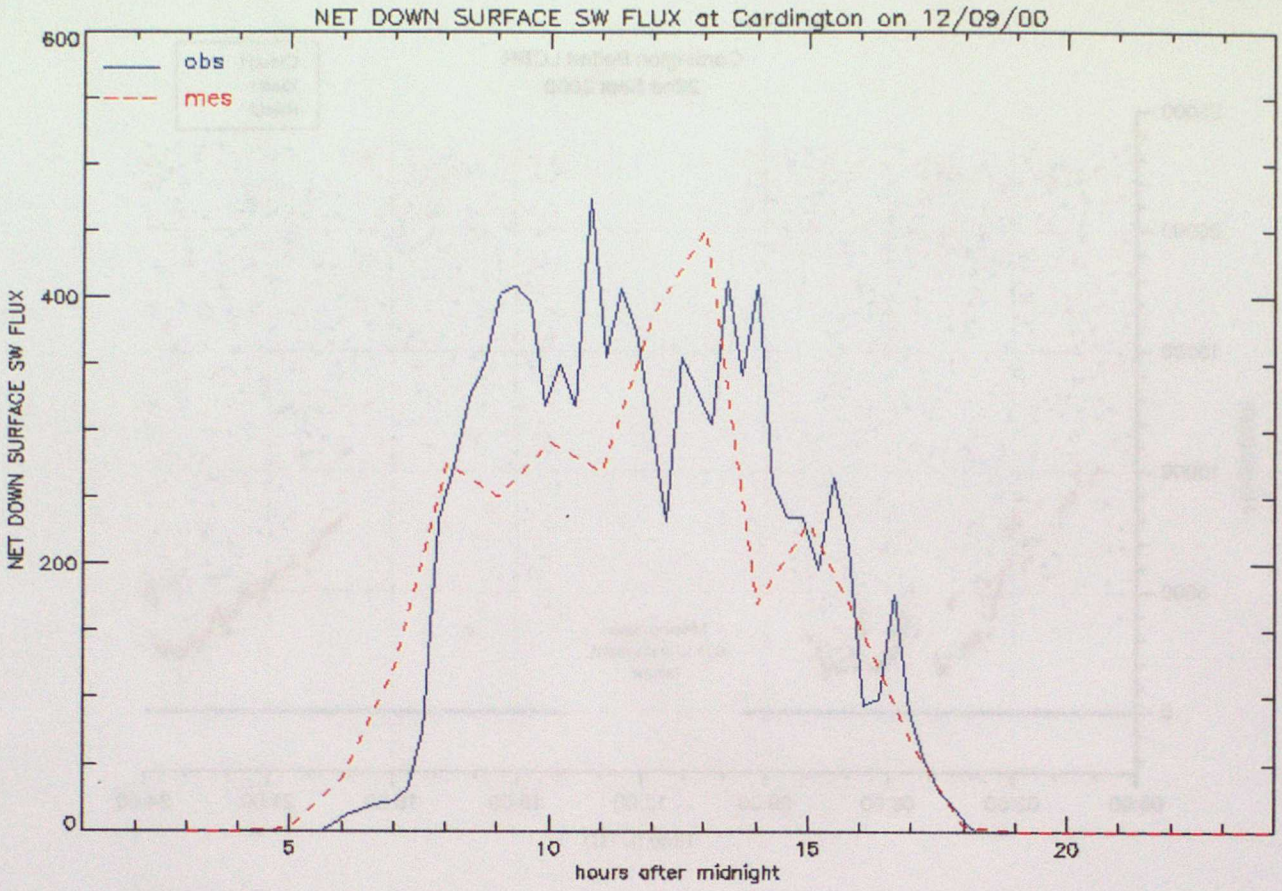


Figure 26: IOP 1 - Model and observed net downwelling SW surface radiation on 12/09/00

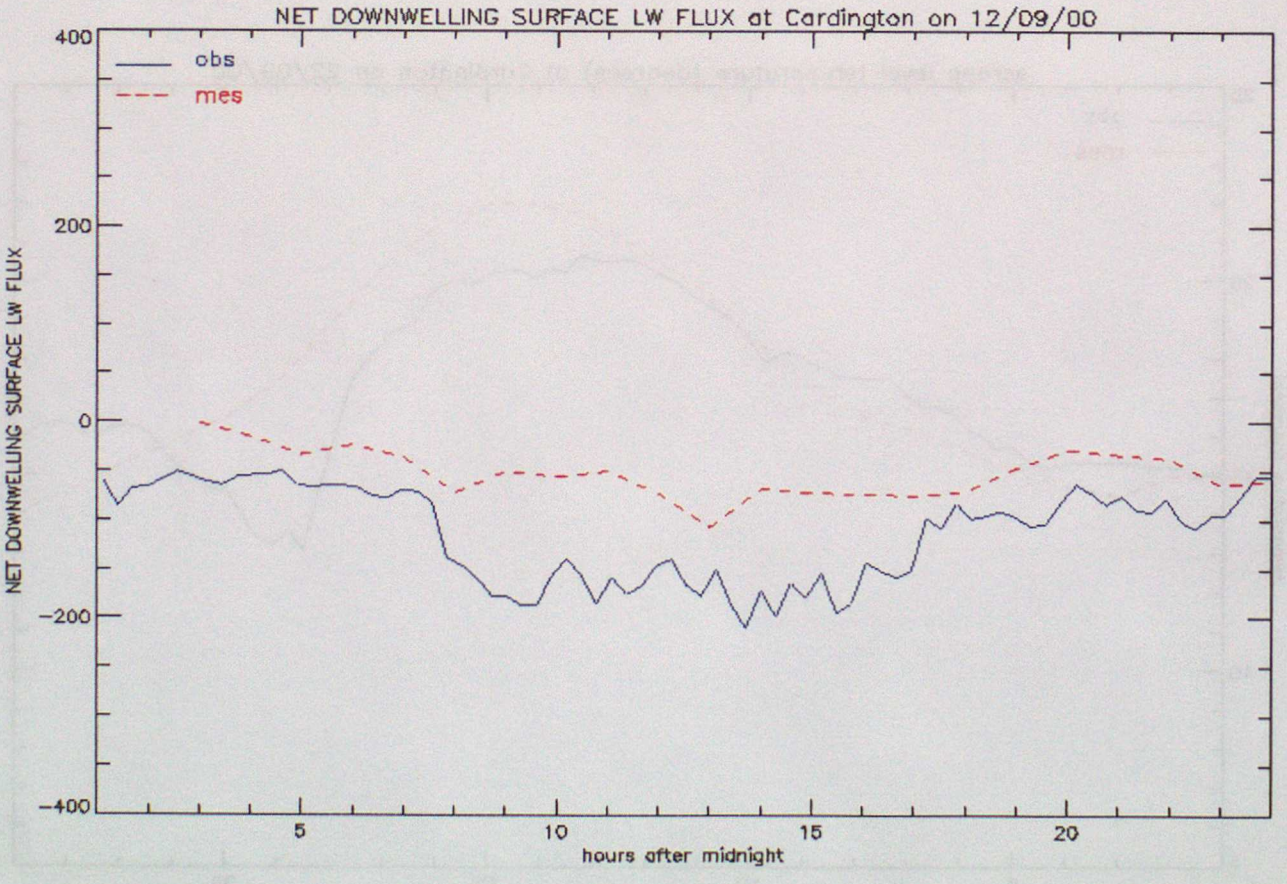
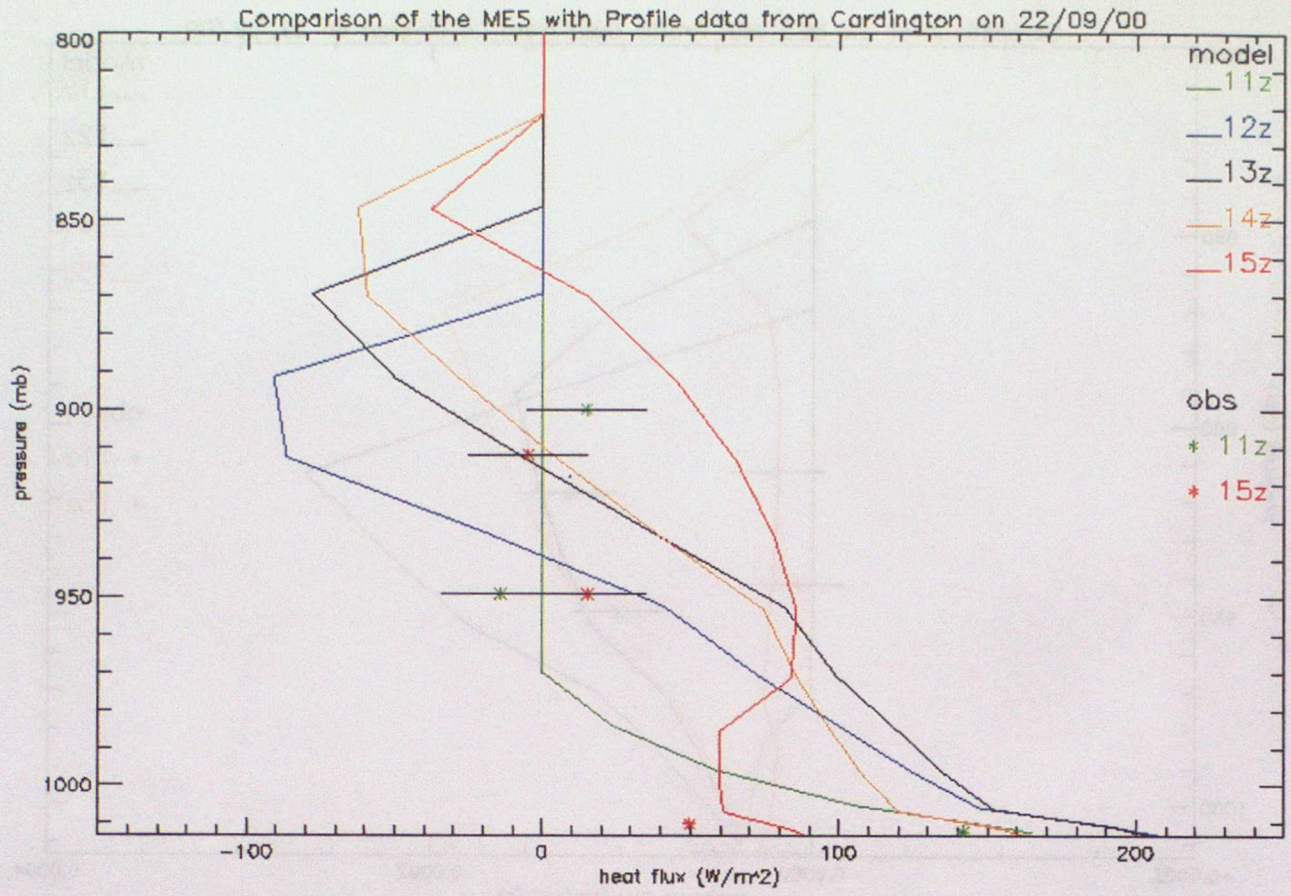


Figure 27: IOP 1 - Model and observed net downwelling LW surface radiation on 12/09/00

(a) sensible heat flux profile



(b) surface sensible heat flux evolution

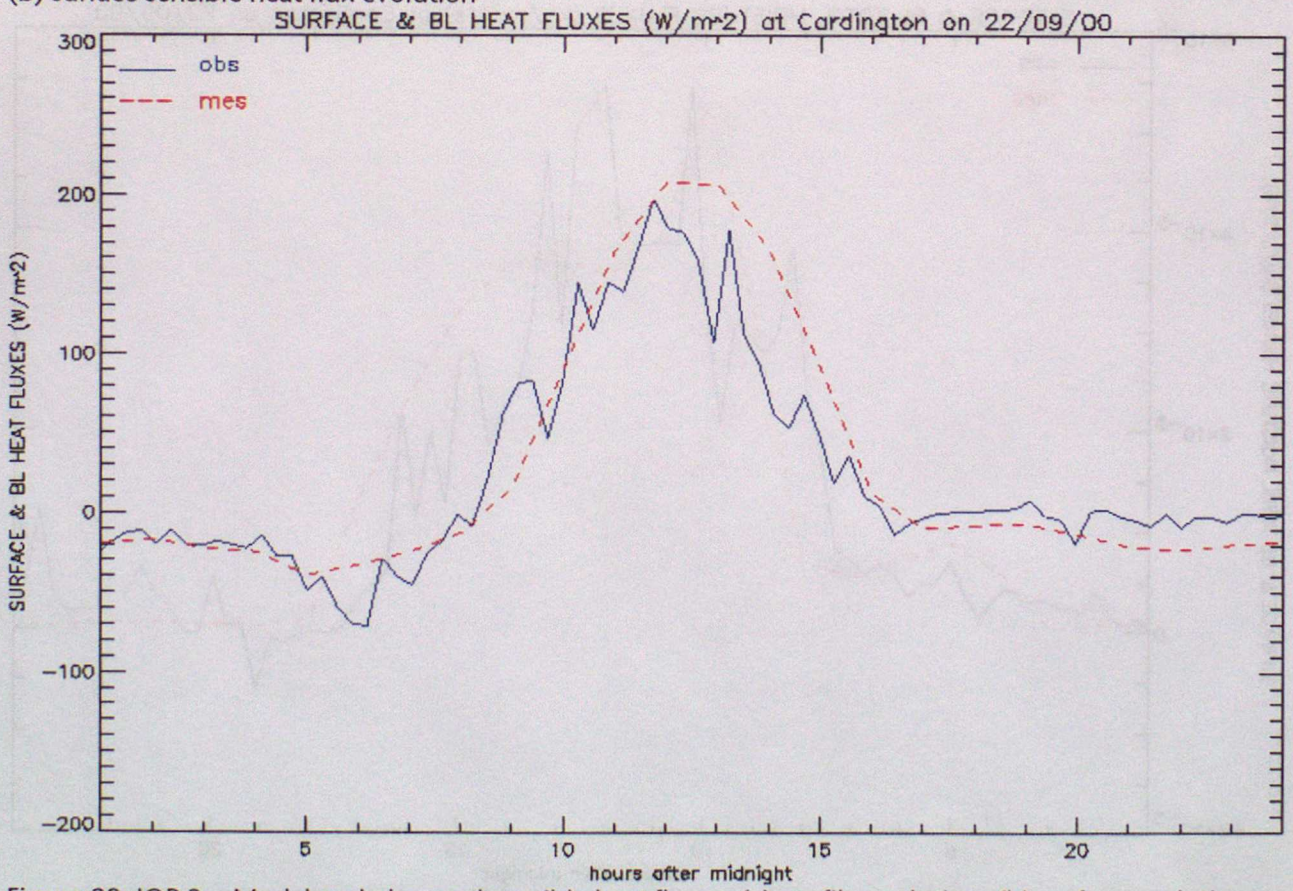
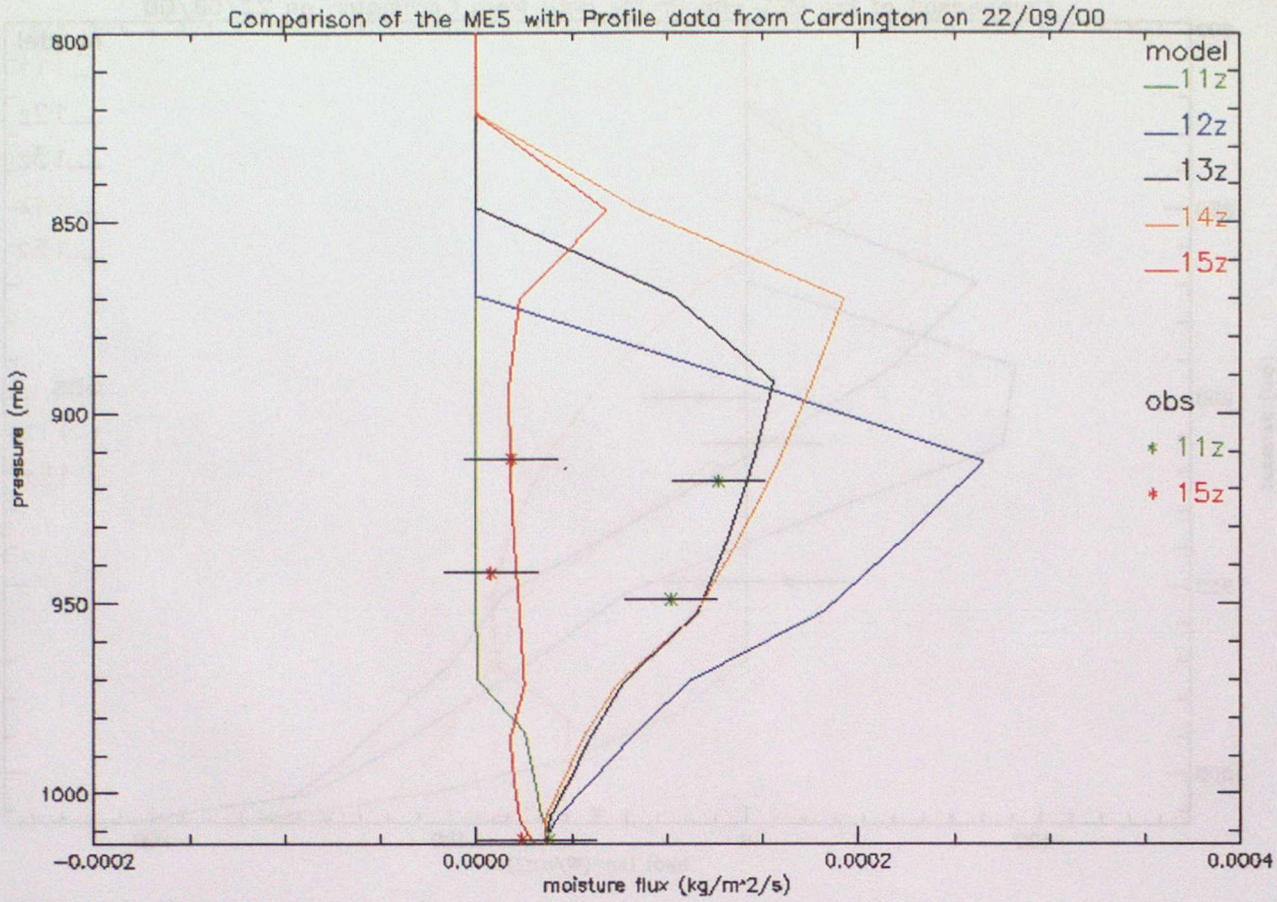


Figure 28: IOP 3 - Model and observed sensible heat fluxes. (a) profile evolution. (b) surface evolution

(a) profile of moisture flux



(b) surface moisture flux

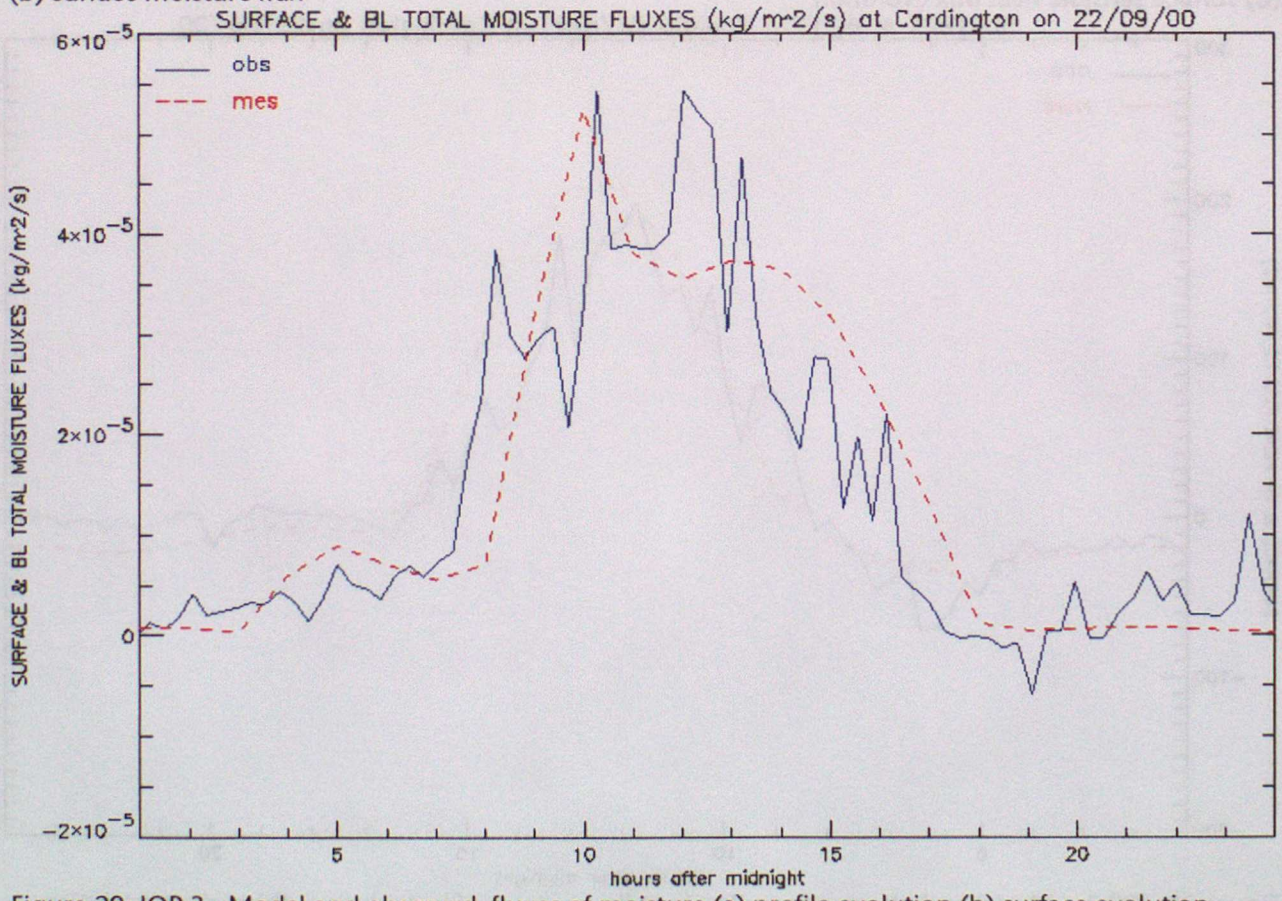


Figure 29: IOP 3 - Model and observed fluxes of moisture (a) profile evolution (b) surface evolution

(a) T+15 (b) T+3

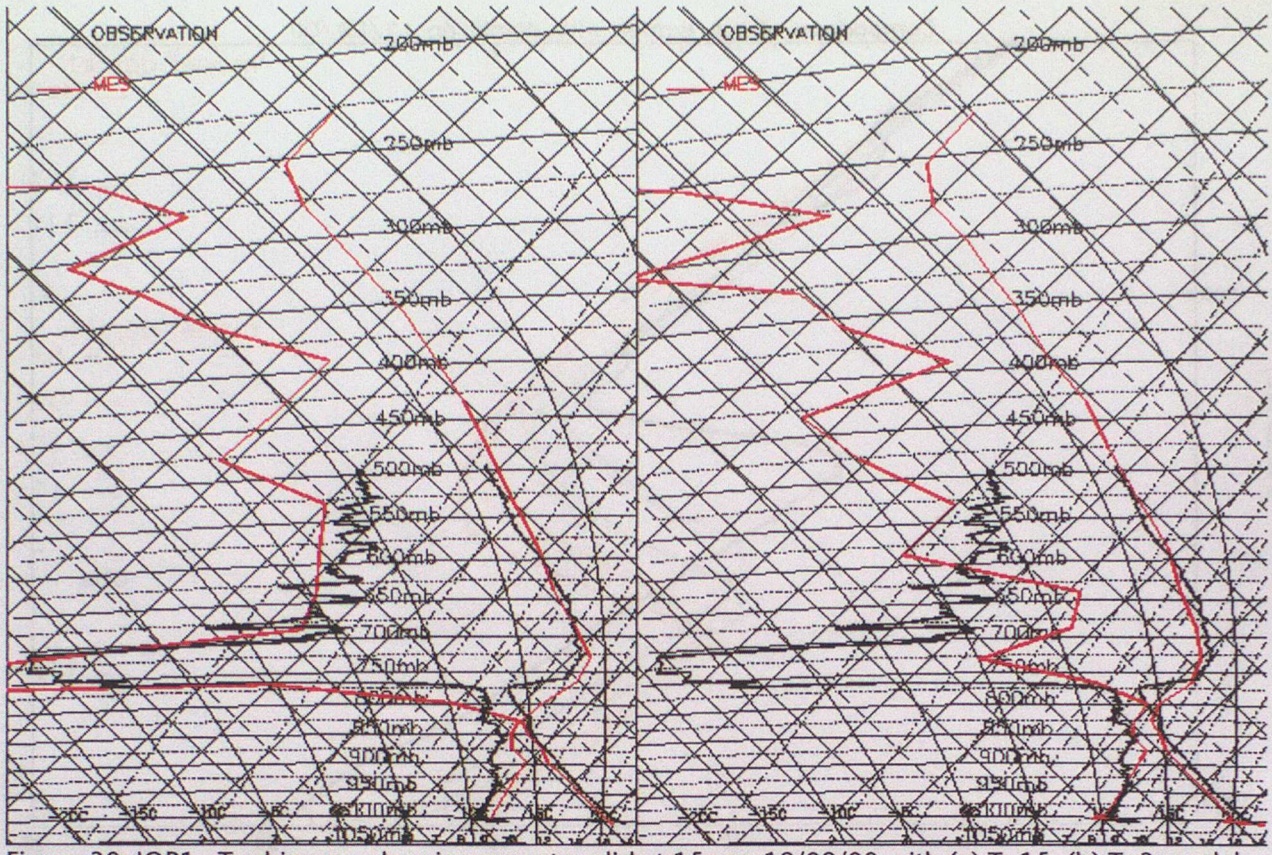


Figure 30: IOP1 - Tephigrams showing ascents valid at 15z on 12/09/00 with (a) T+15, (b) T+3 model profiles overplotted.

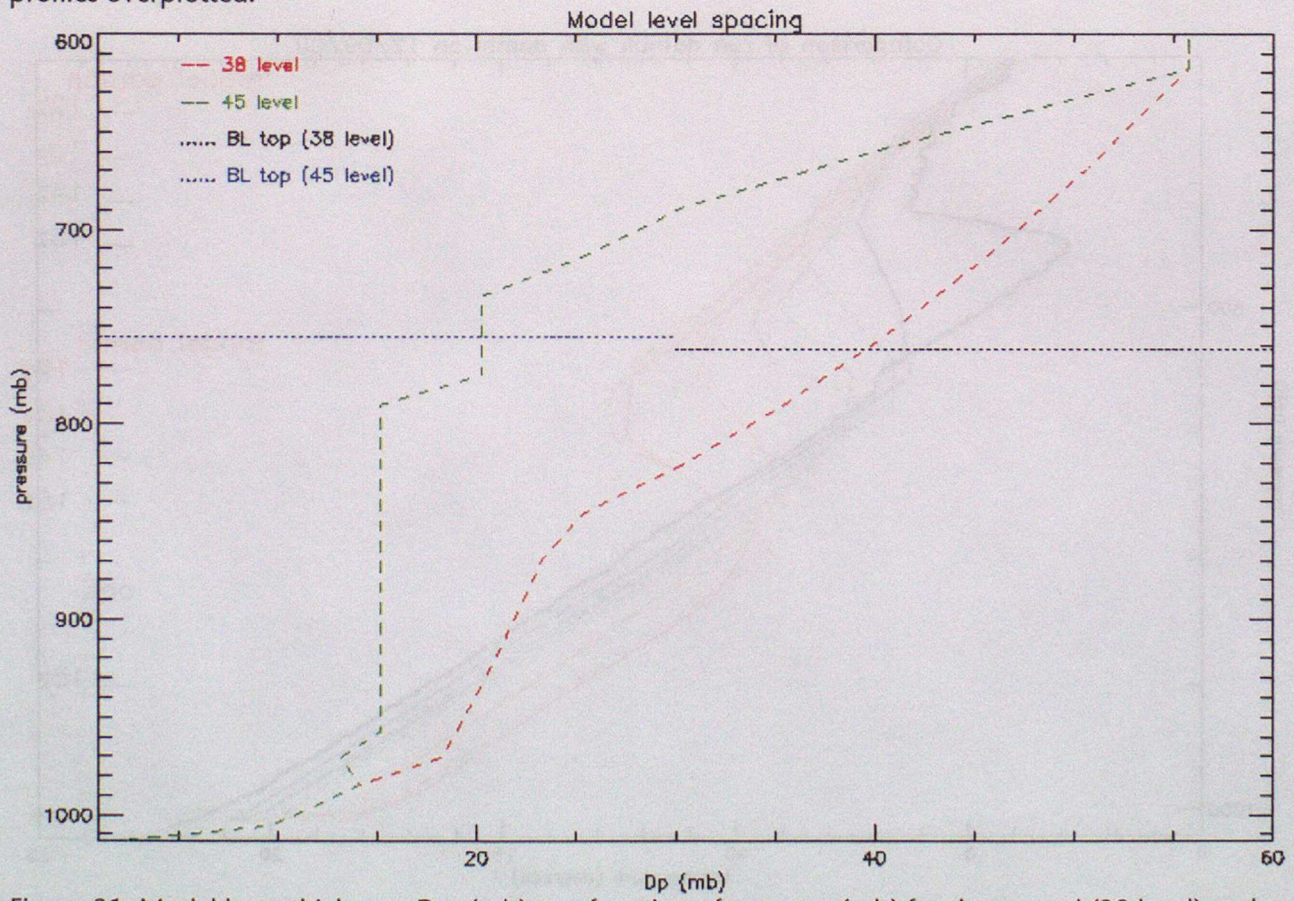
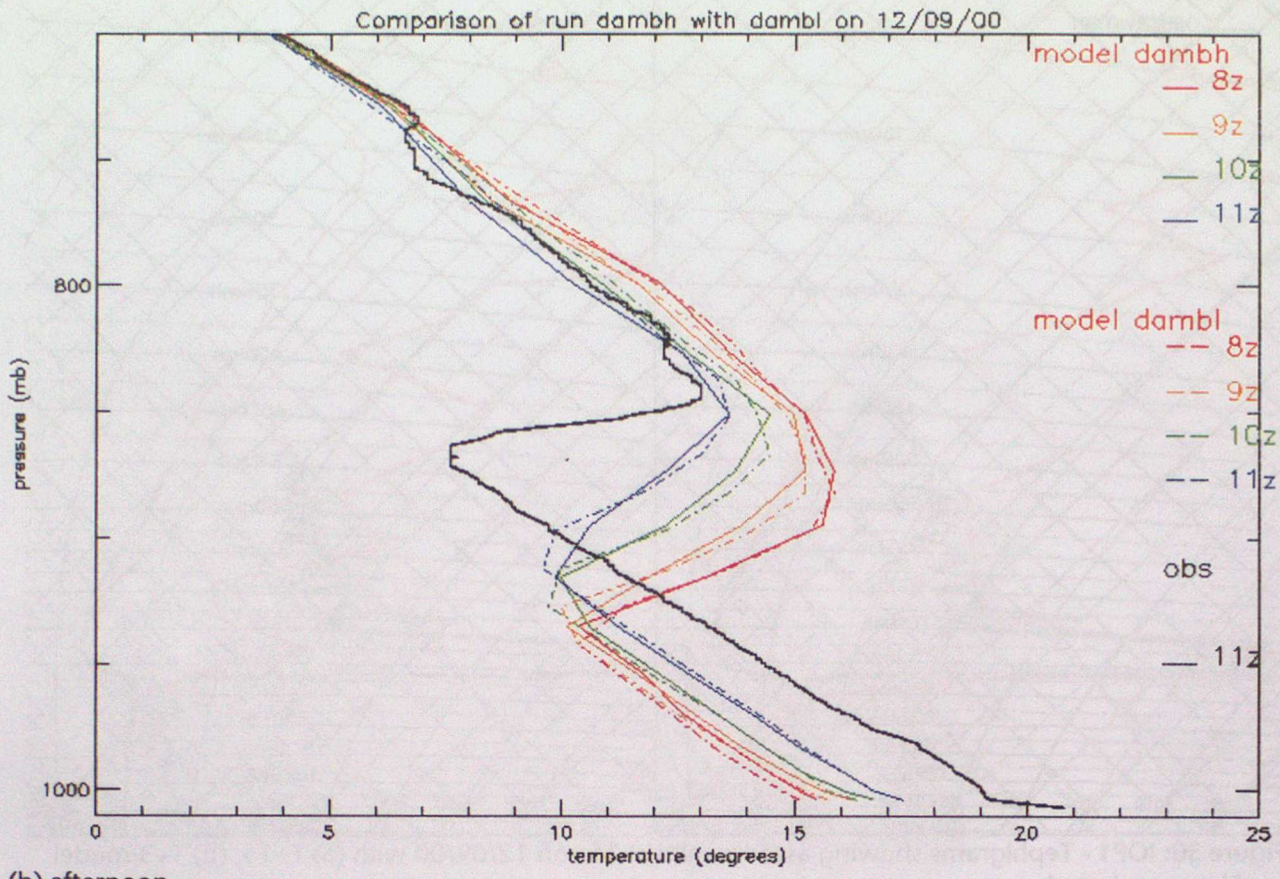


Figure 31: Model layer thickness, Dp, (mb) as a function of pressure (mb) for the control (38 level) and test (45 level) runs. The boundary layer (BL) top (maximum) for both runs is also marked.

(a) morning



(b) afternoon

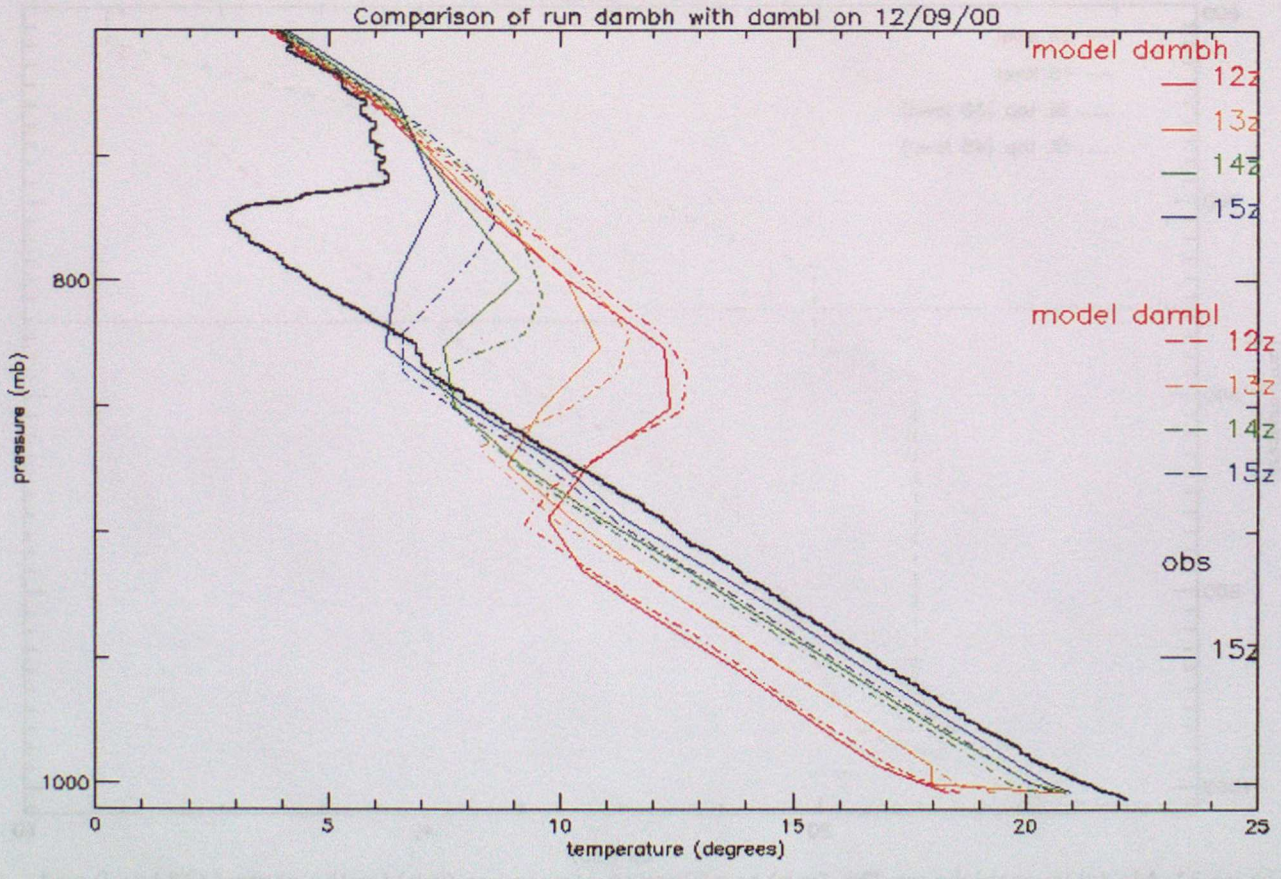
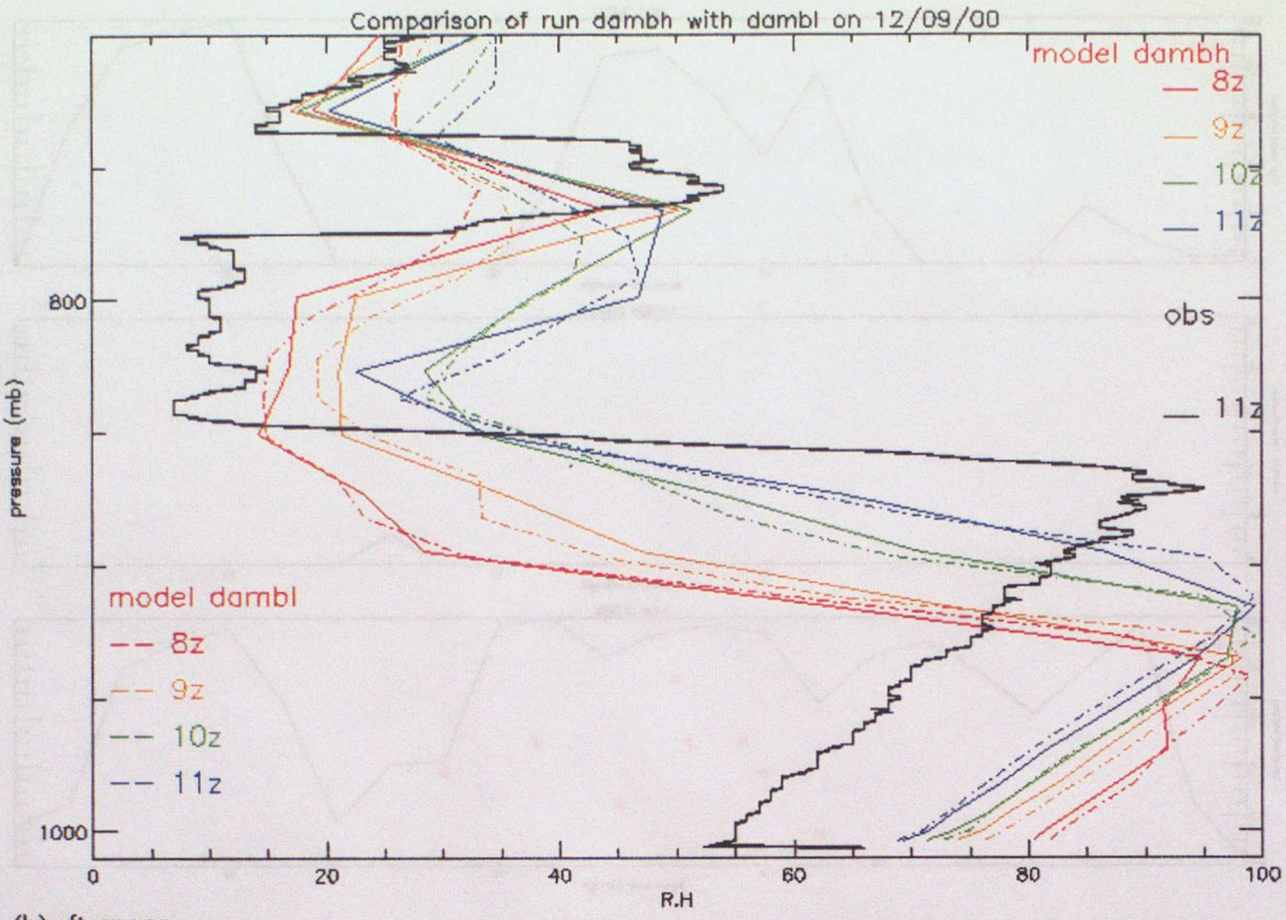


Figure 32: IOP 1 - Model runs dambh (control, solid) and dambl (extra vertical resolution, dashed) and the observed profile during (a) the morning and (b) the afternoon of 12/09/00

(a) morning



(b) afternoon

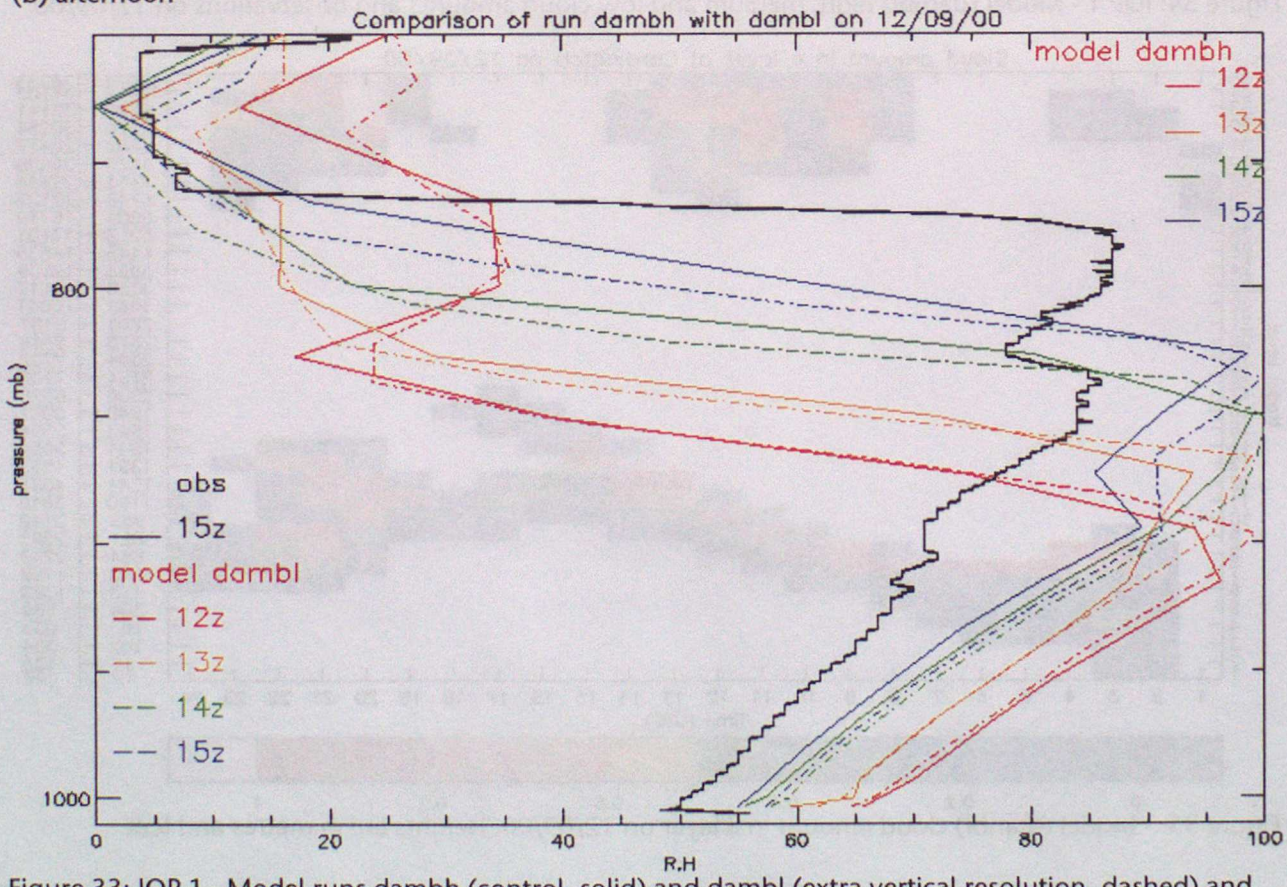


Figure 33: IOP 1 - Model runs dambh (control, solid) and dambl (extra vertical resolution, dashed) and the observed profile during (a) the morning and (b) the afternoon of 12/09/00

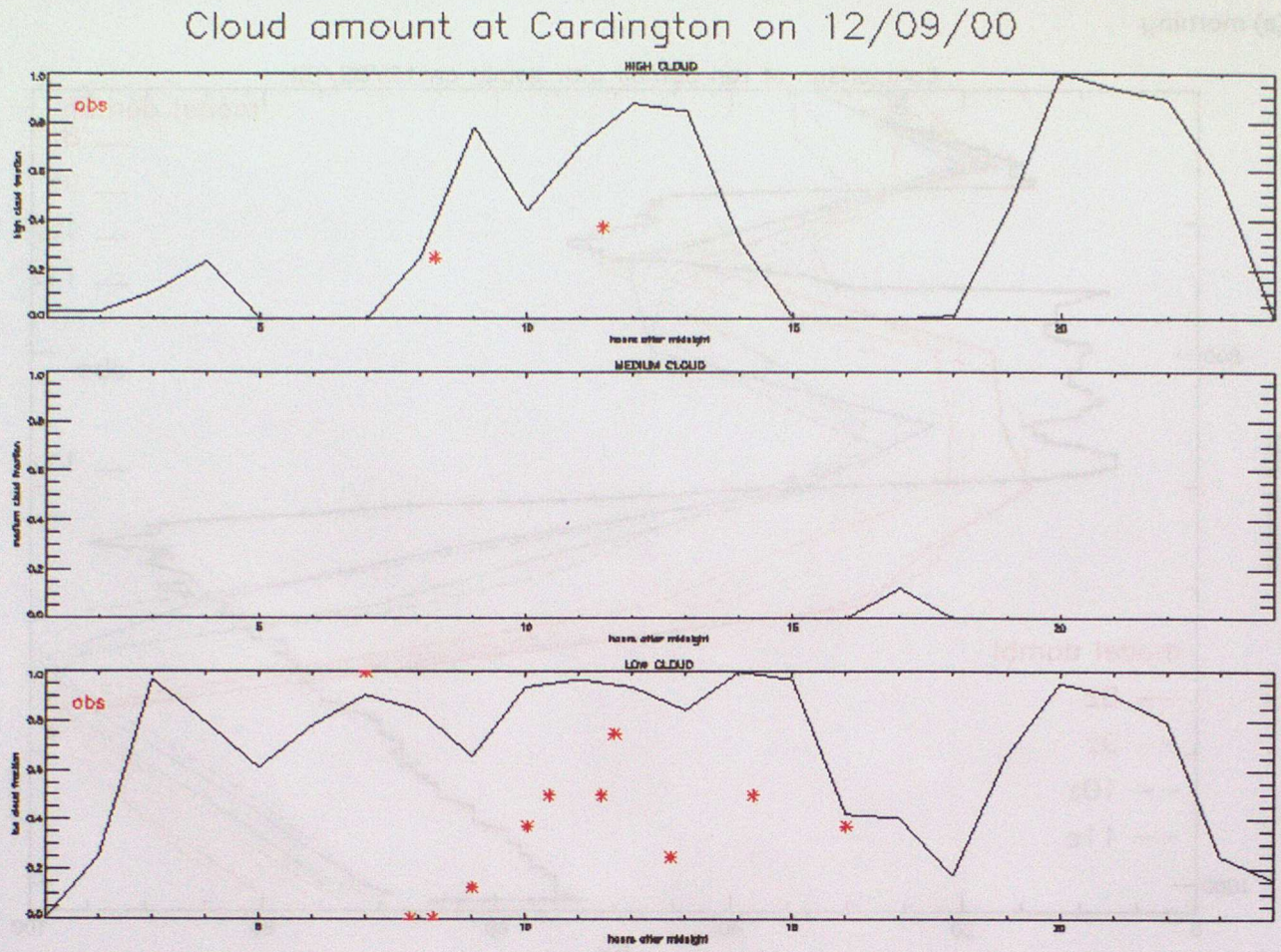


Figure 34: IOP 1 - Model (dambl) high, medium and low cloud amounts and observations on 12/09/00

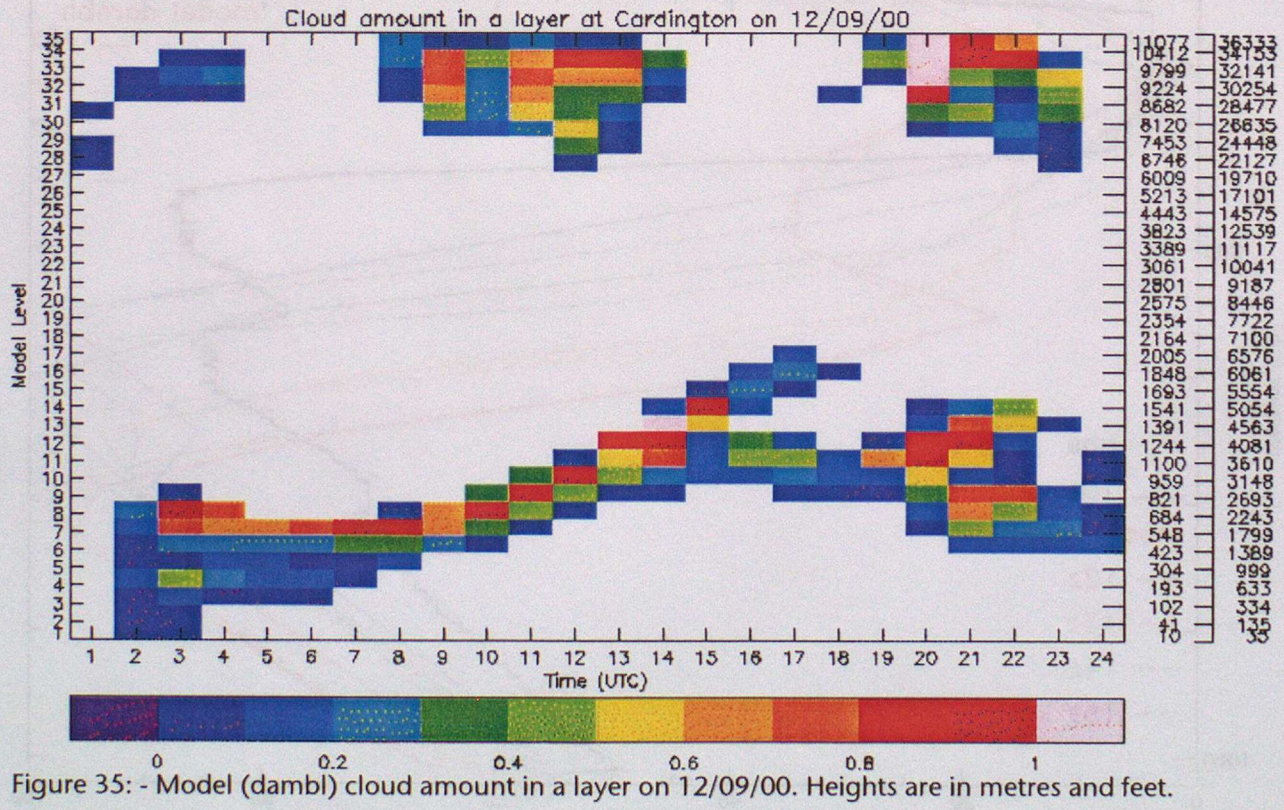


Figure 35: - Model (dambl) cloud amount in a layer on 12/09/00. Heights are in metres and feet.

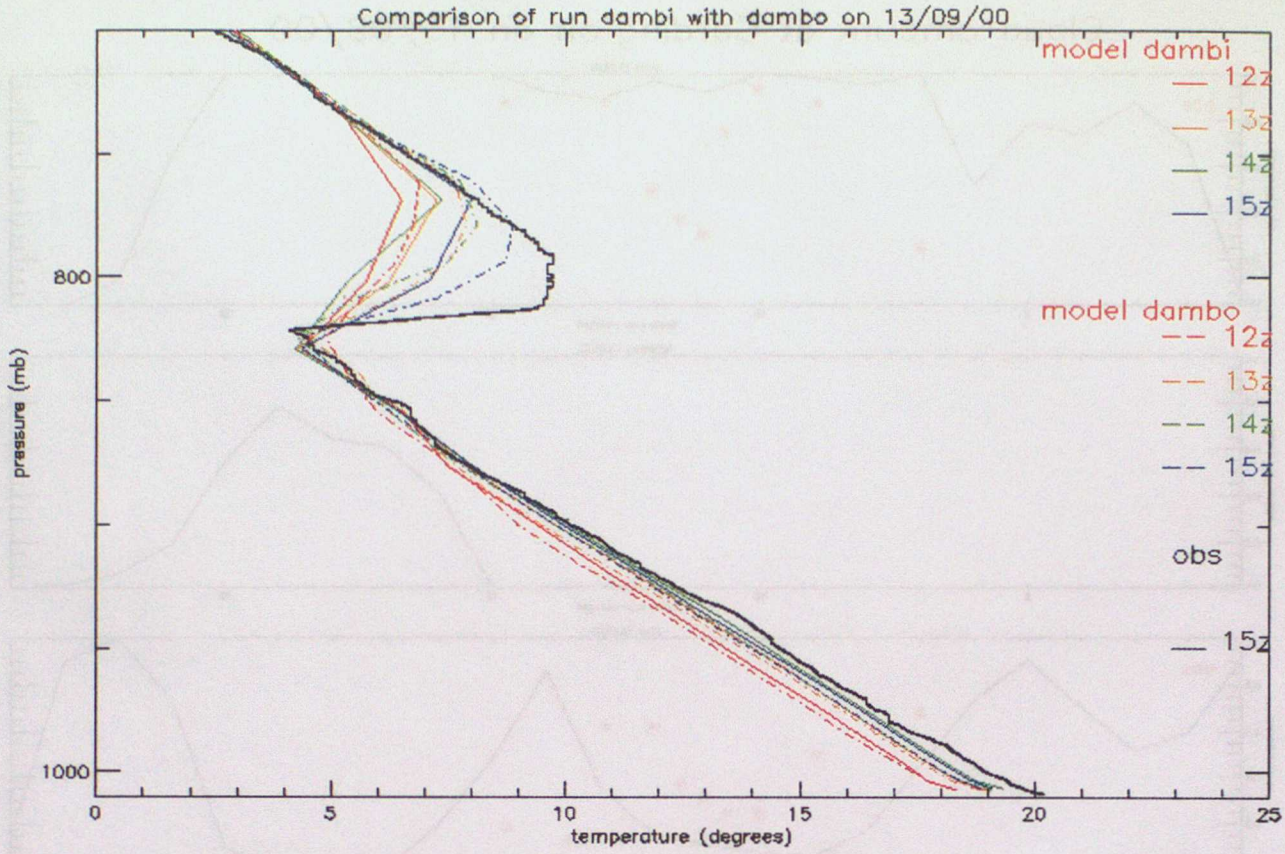


Figure 36: IOP 2 - Model runs dambi (solid) and dambo (dashed) and the observed temperture profile during the afternoon of 13/09/00

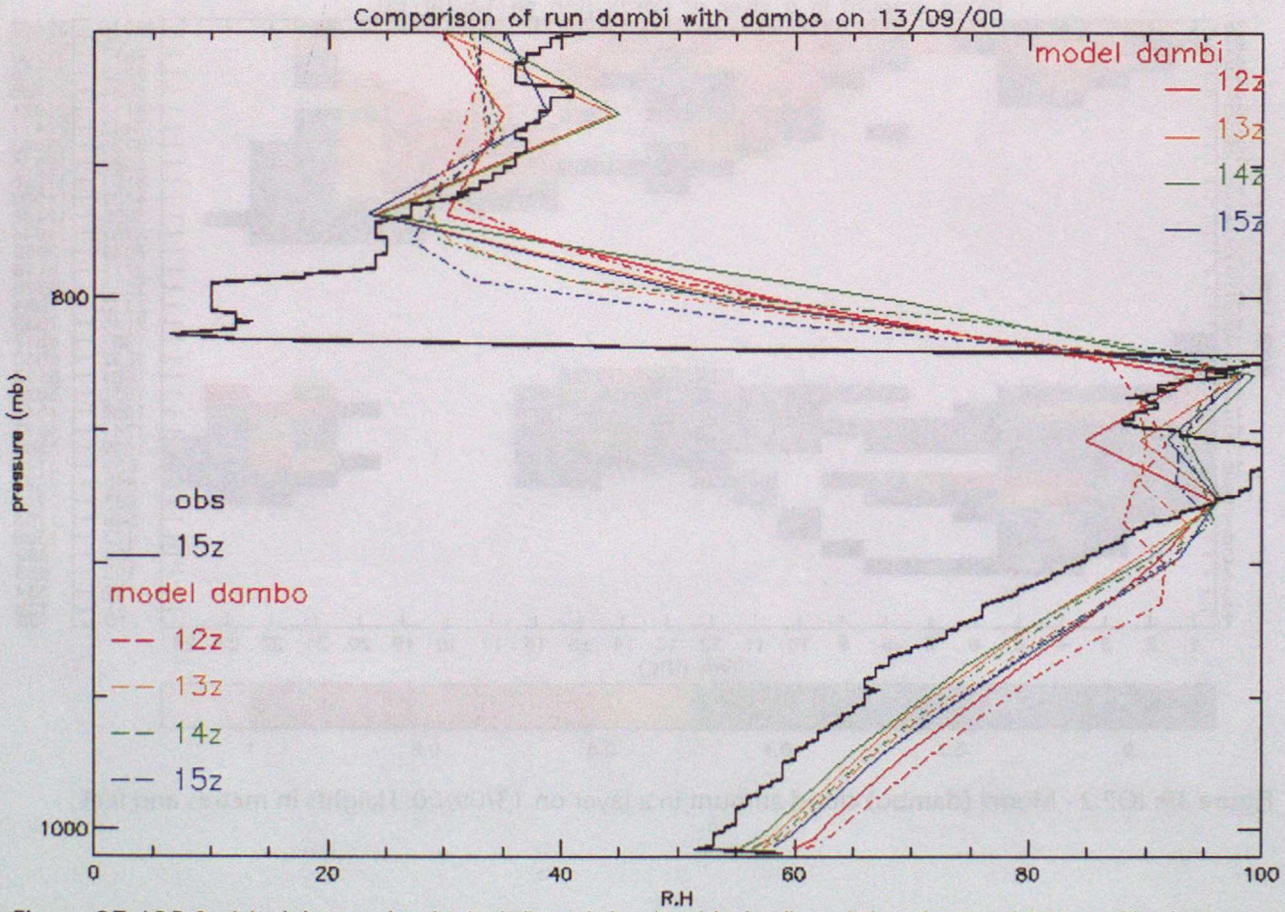


Figure 37: IOP 2 - Model runs dambi (solid) and dambo (dashed) and the observed R.H profile during the afternoon of 13/09/00

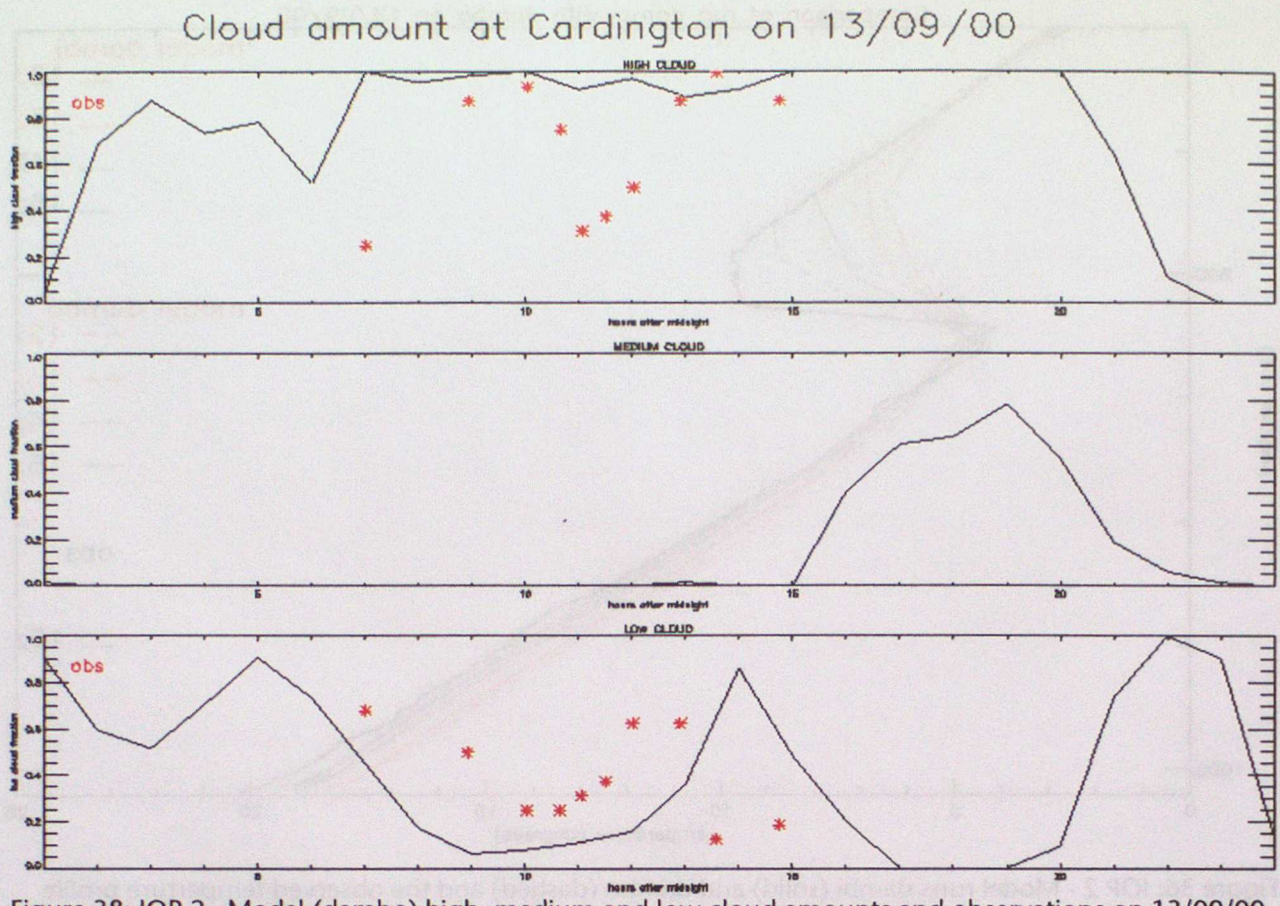


Figure 38: IOP 2 - Model (dambo) high, medium and low cloud amounts and observations on 13/09/00

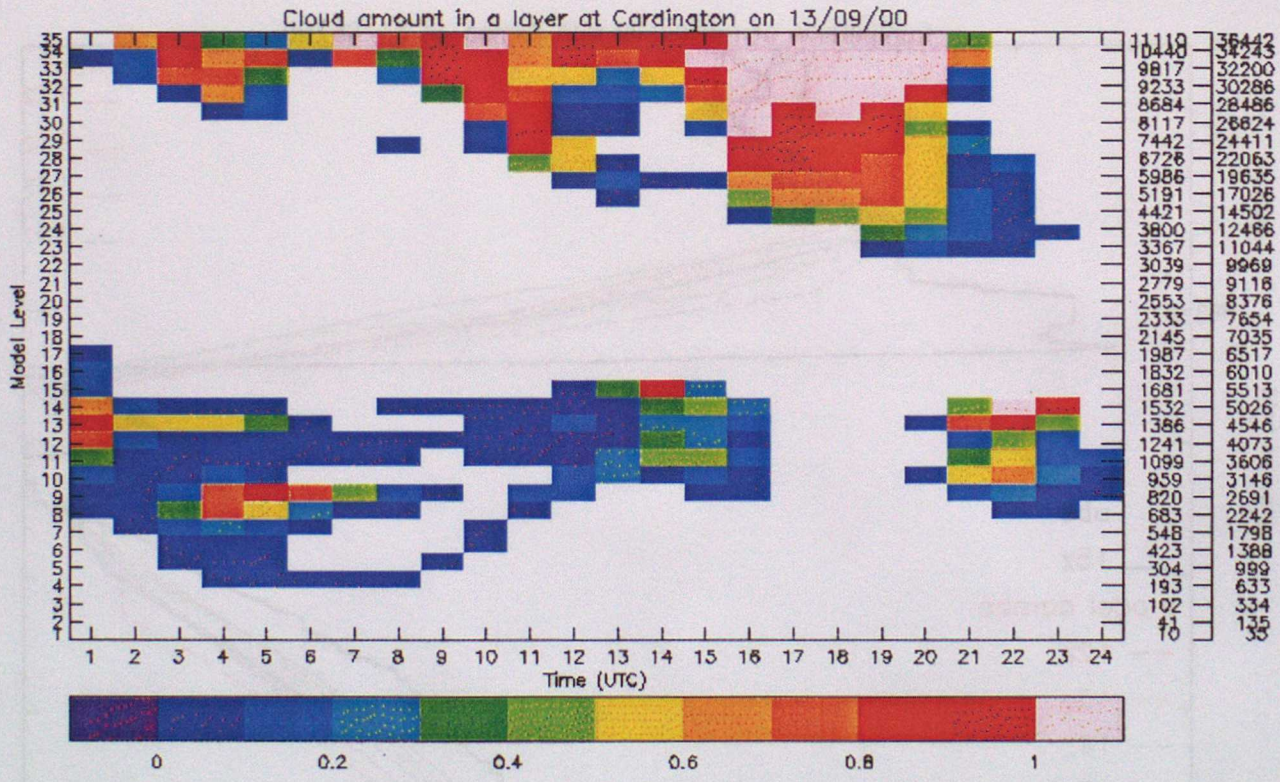


Figure 39: IOP 2 - Model (dambo) cloud amount in a layer on 13/09/00. Heights in metres and feet

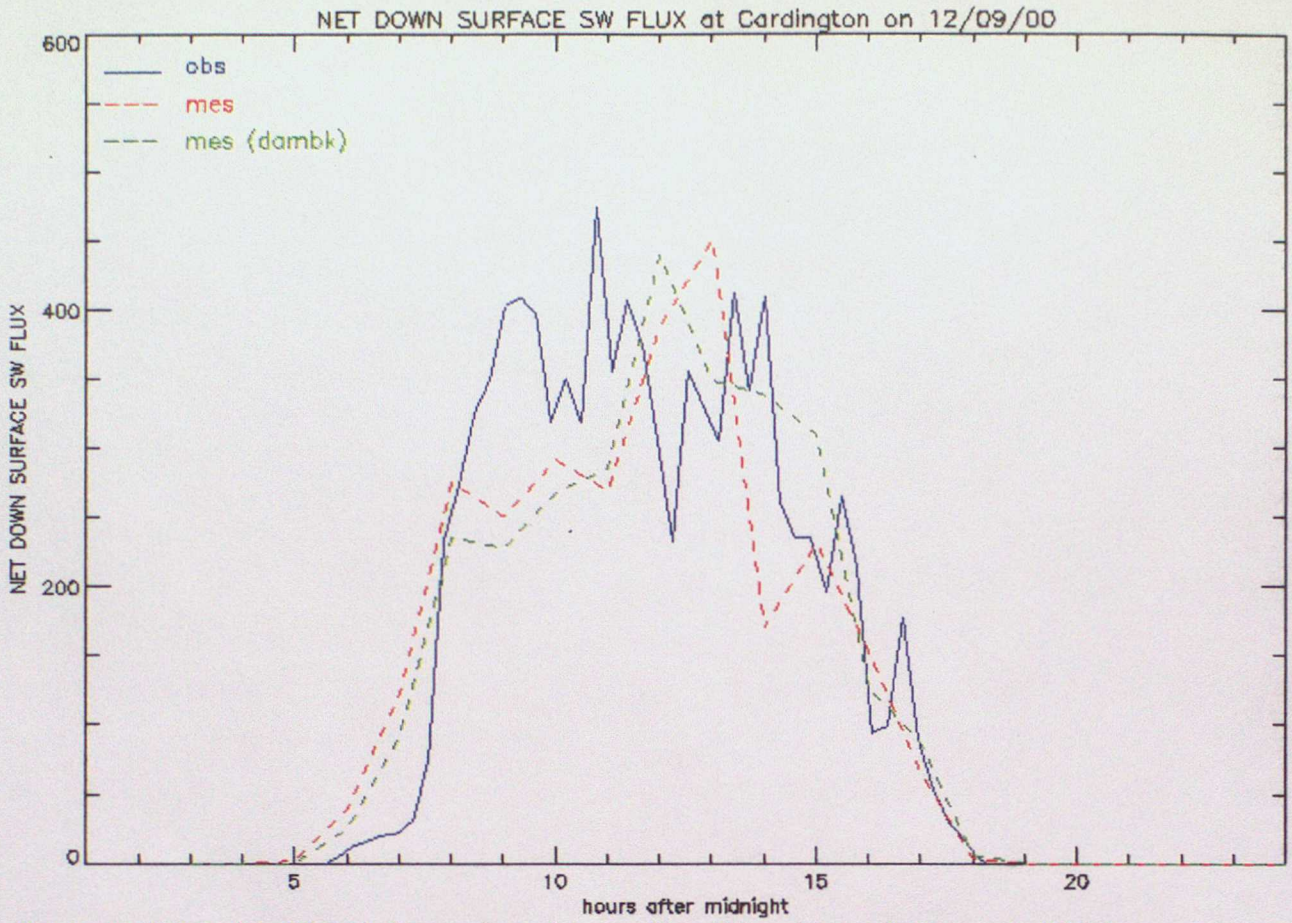


Figure 40: IOP 1 - Model and observed net downwelling SW surface radiation on 12/09/00